– C –

IDL Programs

This appendix reproduces the IDL codes written for some important aspects of the this project including observation planning and data processing.

C.1 CHARA Observations Planning Tool for Survey Projects

C.1.1 Example Input File

```
;IMPORTANT: DO NOT MODIFY THE FORMATTING OF THIS FILE.
;           ENTER YOUR DATA IN RELEVANT PLACES, BUT LEAVE HEADER LINES
;           AND POSITIONING OF THE DATA ELEMENTS UNCHANGED!
;#####################################################################
;#  INPUT FILE FOR CHARA PLAN (BATCH VERSION)                        #
;#  See comments in IDL program chara_planB.pro for a better         #
;#  description of the program.                                      #
;#  Questions? Contact: Deepak Raghavan (raghavan@chara.gsu.edu)     #
;#####################################################################
;
Observing Date (YYYY/MM/DD): 2007/02/15
Wave Band (K, H): K
Minimum observing time required per target (hours): 1.5

START BASELINE/POP LIST
+--------------+----------------+----------------+
| Baseline     |  POPs Tel 1    |  POPs Tel 2    |
| (e.g. S1-E1) |  (e.g. 1,2,3)  |  (e.g. 1,2,3)  |
| Enter your data below, as many lines as needed |
|              |                |                |
| S1-E1        |  1,2,3,4       |  1,2           |
| S1-W1        |  1             |  1             |
| W1-W2        |  1,2           |  1,2,4         |
|              |                |                |
|              |                |                |
+---END-BP-----+----------------+----------------+

START TARGET LIST (HD number or coordinates & epoch)
Enter HD numbers or coordinates & epoch below, one entry per row:
HD number format: nnnnnn; Coordinate/epoch format: hh:mm:ss.ss +dd:mm:ss.s eeee.ee
224930
00:06:36.78 +29:01:17.4 2000.00
000166
039587
07:29:01.77 +31:59:37.8 2000.00
07:54:34.18 -01:24:44.1 2000.00
160346
217107
```

C.1.2 IDL code

```
;#######################################################################
;#  CHARA PLAN (BATCH VERSION)                                         #
;#                                                                     #
;#  An observing prepation tool for the CHARA array                    #
;#  Original Version: January 3, 2007                                  #
;#  Deepak Raghavan (raghavan@chara.gsu.edu)                           #
;#                                                                     #
;#  For a given observing date, filter, set of baselines, POPs, and a  #
;#  set of HD numbers, this program will create an output file of the  #
;#  subset of targets, baselines, and POPs that can be observed for at #
;#  least a specified number of hours during the night.  A target is   #
;#  considered observable at times between dusk and dawn when its      #
;#  altitude is greater than 30 degrees and the optical path length    #
;#  difference between the two telescopes is less than the maximum     #
;#  range that the OPLE carts can compensate for.                      #
;#  Most of the logic in CHK_AVAIL was borrowed from Jason             #
;#  Aufdenbereg's CHARA_PLAN program, with modifications and           #
;#  enhancements as required.                                          #
;#                                                                     #
;#  Input: Specified in chara_planB.inp (see that file for formatting) #
;#  Output: chara_planB.out                                            #
;#  NOTE: Input file must be in current directory from where you run   #
;#        the IDL program!  The output file will also be created in    #
;#        same directory.                                              #
;#  CAUTION: If a file with same name as output file exists in current #
;#           directory, it will be overwritten!                        #
;#                                                                     #
;#  Maintenance Log:                                                   #
;#  ***************                                                    #
;#     1/25/07  Fixed bug to account for non-consecutive delay/alt avl #
;#        e.g. if delay is avail from 2:00 - 3:30 and then again from  #
;#        6:00 - 6:30, the old version assumed avail from 2:00 - 6:30! #
;#                                                                     #
;#######################################################################
pro chara_planB  ; CHARA_PLAN_BATCH

;
;  Comon variables to share with chk_avail
;

common CHARA, TELESCOPES, BASELNAME, POPS
common params, year_obs, month_obs, day_obs, wave_band, min_obst


;#
;#  SETUP CHARA CONSTANTS
;#

TELESCOPES = ['S1','S2','E1','E2','W1','W2'] ; Tels are numbered 0 - 5
BASELNAME = ['S1S2','E1E2','W1W2','W2E2','S2W2','S1W2','E1W2','S2E2',$
             'S2W1','W1E2','S1W1','S1E2','S2E1','E1W1','S1E1'] ; Baselines are numbered 0 - 14
POPS = [1,2,3,4,5]

;  Non CHARA-related constants:

MAX_HD = 359083  ; Maximum HD number from 1949 extension of the catalog

;#
;#  READ INPUT FILE TO GET PARAMETERS
;#
openr,1,'./chara_planB.inp'

input = '; '  ; Read and ignore header lines; read first data line
while (NOT EOF(1)) do begin
      readf,1,input
      if (STRMID(input,0,1) NE ';') then BREAK ; First data line found
endwhile

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (1)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;
;#  Extract observing date
;
work = strsplit(input,':',/extract)
```

```
if (work(0) NE 'Observing Date (YYYY/MM/DD)') then begin
   print,'Invalid first line of data (after header lines)!'
   print,'  You entered  : ', input
   print,'  Valid example: ', 'Observing Date (YYYY/MM/DD): 2007/02/15'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

work2 = strsplit(work(1),'/',/extract)
year_obs = work2(0) * 1
month_obs = work2(1) * 1
day_obs = work2(2) * 1

;  Validate date: Not perfect, but good enough!
;  If folks are still using this program after 2050, we have BIG problems!
;
if (year_obs LT 2000 OR year_obs GT 2050 OR $
    month_obs LT 1 OR month_obs GT 12 OR $
    day_obs LT 1 OR day_obs GT 31) then begin
   print,'Invalid observing date entered!'
   print,'  You entered date as: ', work(1)
   print,'  It should be in YYYY/MM/DD format'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;
;#  Extract and validate observing wave band
;
readf,1,input
if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (2)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

work = strsplit(input,':',/extract)
if (work(0) NE 'Wave Band (K, H)') then begin
   print,'Invalid second line of data (after header lines)!'
   print,'  You entered  : ', input
   print,'  Valid example: ', 'Wave Band (K, H): K'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

wave_band = work(1)
rmv_blank,wave_band
if (wave_band NE 'K' AND wave_band NE 'H') then begin
   print,'Invalid Wave Band value entered'
   print,'  You entered: ', wave_band
   print,'  Valid values are K or H'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;
;#  Extract and validate minimum observing time per target (hours)
;
readf,1,input
if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (3)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

work = strsplit(input,':',/extract)
if (strmid(work(0),0,11) NE 'Minimum obs') then begin
   print,'Invalid third line of data (after header lines)!'
   print,'  You entered  : ', input
   print,'  Valid example: ', 'Minimum observing time required per target (hours): 1.5'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
```

```
endif

min_obst = work(1) * 1.  ; Minimum observing time per target (hours)
if (min_obst LE 0 OR min_obst GE 10) then begin
   print,'Invalid minimum observing time entered'
   print,'  You entered: ', min_obst
   print,'  Value must be greater than zero and less than 10'
   print,'  Default value of 1.5 hours assumed'
   min_obst = 1.5
endif

;#
;#  Extract Baselines & POPs from input list
;#

while (NOT EOF(1)) do begin   ; skip to "start baseline/pop list"
      readf,1,input
      if (STRMID(input,0,10) EQ 'START BASE') then BREAK  ; Start found
endwhile

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (4)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

i = 0
while (NOT EOF(1)) do begin   ; skip 4 comment lines
      readf,1,input
      i = i + 1
      if (i GE 4) then BREAK  ; 4 lines skipped
endwhile

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (5)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;
;  Start gathering baseline/POP data
;
nbr_bl = 0
maxnbl = size(BASELNAME,/dimensions)  ; Get maximum number of baselines possible
inp_tel1a = strarr(maxnbl)
inp_tel2a = strarr(maxnbl)
inp_pop1a = intarr(maxnbl,5)
inp_pop2a = intarr(maxnbl,5)
;
;#  Begin baseline/POP loop
;
while (NOT EOF(1)) do begin

    readf,1,input  ; Read baseline/POP data line
    if (STRMID(input,0,10) EQ '+---END-BP') then BREAK ; end of BL/POP data

    work = strsplit(input,'|',/extract)
    nelem = size(work,/dimensions)
    If (nelem(0) NE 3) then begin
       print,'Invalid baseline,POP data line'
       print,'  You entered  : ', input
       print,'  Valid example: ', '| S1-E1        |  1,2,3,4,5     |  1,2,3,4,5     |'
       print,'  This data line will be ignored'
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

;
;   3 elements found as required (baseline, pop1, pop2), so proceed...
;

;
;  Extract and validate telescopes
;
    ibase = work(0)
    rmv_blank,ibase
    ipop1 = work(1)
    rmv_blank,ipop1
```

```
    ipop2 = work(2)
    rmv_blank,ipop2
    if (ibase EQ '' AND ipop1 EQ '' AND ipop2 EQ '') then $
       CONTINUE ; Skip bkank line, go to next iteration of baseline/POP loop

    itel = strsplit(ibase,'-',/extract)
    ntel = size(itel,/dimensions)
    if (ntel(0) NE 2) then begin  ; Two telescopes found?
       print,'Baseline format invalid'
       print,'  You entered  : ', input
       print,'  Valid example: ', '| S1-E1        |  1,2,3,4,5     |  1,2,3,4,5     |'
       print,'  This data line will be ignored'
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

    itel1 = itel(0)
    t1 = where(TELESCOPES EQ itel1) ; Set numeric value of Tel 1
    if (t1(0) EQ -1) then begin   ; Invalid Tel 1
       print,'Invalid value for Telescope 1: ', itel1
       print,'  In data line: ', input
       print,'  Valid values are: S1, S2, E1, E2, W1, W2'
       print,'  This data line will be ignored'
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

    itel2 = itel(1)
    t2 = where(TELESCOPES EQ itel2) ; Set numeric value of Tel 2
    if (t2(0) EQ -1) then begin   ; Invalid Tel 2
       print,'Invalid value for Telescope 2: ', itel2
       print,'  In data line: ', input
       print,'  Valid values are: S1, S2, E1, E2, W1, W2'
       print,'  This data line will be ignored'
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

    if (itel1 EQ itel2) then begin ; Tel 1 & 2 can not be the same!
       print,format='("Telescope 1 and 2 have same value!: ",A2,", ",A2)', itel1, itel2
       print,'  In data line: ', input
       print,'  Choose different telescope values'
       print,'  This data line will be ignored'
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

;
;   Extract and validate pop1 & pop2
;
    errdata = 'N'

    for i = 1, 2 do begin  ; Process POP1 and POP2 lists

        ipop = strsplit(work(i),',',/extract)
        npop = size(ipop,/dimensions)
        if (npop(0) LT 1 OR npop(0) GT 5) then begin  ; Invalid number of pops
           print,format='("POP ",I1, " format invalid")', i
           print,'  You entered: ', input
           print,'  Enter upto 5 POPs, comma demilited'
           print,'  This data line will be ignored'
           errdata = 'Y'
           BREAK ; Exit FOR loop and proceed to process next data line
        endif

        for j = 0, 4 do begin ; Always load array with 5 elements (0 fill at end)

            if (j GE npop(0)) then begin  ; Zero fill at end of array
               curpops = [curpops, 0]
               CONTINUE
            endif

            ipop(j) = ipop(j) * 1
            if (ipop(j) LT 1 OR ipop(j) GT 5) then begin ; Invalid pop number
               print,format='("POP number ",I1, " for POP-", I1, " invalid: ",I2)',j+1,i,ipop(j)
               print,'  In data line: ', input
               print,'  POP numbers must be between 1 & 5'
               print,'  This data line will be ignored'
               errdata = 'Y'
               BREAK ; Exit FOR loop and proceed to process next data line
            endif
;
;           Save valid POP in array
```

```
;
            if (j EQ 0) then curpops = ipop(j) $
            else curpops = [curpops, ipop(j)]

        endfor ; for loop for 5 elements ends

        if (errdata EQ 'Y') then BREAK ; Skip to next baseline/POP data

        if (i EQ 1) then curpops1 = curpops $
        else curpops2 = curpops

    endfor  ; for loop for 2 POPs ends

    if (errdata EQ 'Y') then CONTINUE ; Skip to next baseline/POP data

    nbr_bl = nbr_bl + 1
    bli = nbr_bl - 1
    if (nbr_bl GT maxnbl) then begin  ; Can only process 25 baselines
       print,'Cannot process more than 25 valid baseline/POP data lines'
       print,'  Will ignore input: ', input
       CONTINUE ; Skip to next iteration of baseline/POP loop
    endif

    inp_tel1a(bli) = itel1
    inp_tel2a(bli) = itel2
    inp_pop1a(bli,*) = curpops1
    inp_pop2a(bli,*) = curpops2

endwhile
;
;#  END baseline/POP loop
;

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (6)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

if (nbr_bl EQ 0) then begin          ; No valid baselines found
   print,'No valid baseline/POP found!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;#
;#  Extract HD numbers and/or coordinates from input list
;#

while (NOT EOF(1)) do begin   ; skip to "start target list"
      readf,1,input
      if (STRMID(input,0,12) EQ 'START TARGET') then BREAK  ; Start found
endwhile

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (7)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

i = 0
while (NOT EOF(1)) do begin   ; skip 2 comment lines
      readf,1,input
      i = i + 1
      if (i GE 2) then BREAK  ; 2 lines skipped
endwhile

if (EOF(1)) then begin          ; Premature end of file!
   print,'End of input file reached before required data gathered (8)!'
   print,'  Please fix the input file and rerun this program'
   close,1
   goto, done
endif

;
;  Gather target HD/coords into an array
```

```
;

nbr_tar = 0
restore,'/usr/local/rsi/idl_lib/CHARA_PLAN_V1.2/hipp_ra_dec_hd_spec.sav' ; Restore HIPPARCOS catalog
while (NOT EOF(1)) do begin

      readf,1,input
;
;  If colon found in data, treat as coordinates, else treat as HD number
;
      work = strsplit(input,':',/extract)
      nelem = size(work,/dimensions)
      If (nelem(0) LE 1) then begin    ; HD number as no colon found

         curhd = input * 1.
;
;     Validate HD number range and against HIP catalog
;
         if (curhd LE 0 OR curhd GT MAX_HD) then begin  ; Invalid HD number
            print,'Invalid HD number specified: ', curhd
            print,'  In data line: ', input
            print,'  Valid values are between 1 and ', MAX_HD
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of HD loop
         endif

         hipind = where(hipp_hd eq curhd)
         if (hipind(0) eq -1) then begin  ; star not in Hipparcos catalog
            print,format='("Cannot find coordinates for HD ",I6," in HIPPARCOS catalog")', curhd
            print,'  In data line: ', input
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of HD loop
         endif

         irad = hipp_ra(hipind(0))    ; HIP RA in degrees
         idecd = hipp_dec(hipind(0))  ; HIP DEC in degrees
         iepoc = 1991.25              ; Epoch of HIP coordinates


      endif else begin                 ; Coordinates entered

         curhd = 0.
         work = strsplit(input,' ',/extract)  ; Extract RA, DEC, Epoch
         nelem = size(work,/dimensions)
         If (nelem(0) LT 3) then begin    ; 3 elements not found (ra, dec, epoch)
            print,'Coordinates format is invalid'
            print,'  You entered  : ', input
            print,'  Valid example: ', '07:01:38.10 +48:22:47.0 2000.0'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of target loop
         endif

         ira = work(0)  ; Input RA
         idc = work(1)  ; Input Dec
         iep = work(2)  ; Input Epoch
;
;        Extract RA and convert to decimal degrees
;
         work = strsplit(ira,':',/extract)
         nelem = size(work,/dimensions)
         If (nelem(0) NE 3) then begin    ; 3 elements not found (rah, ram, ras)
            print,'Coordinate RA format is invalid'
            print,'  You entered  : ', input
            print,'  Valid example: ', '07:01:38.10 +48:22:47.0 2000.0'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of target loop
         endif

         irah = work(0) * 1
         iram = work(1) * 1
         iras = work(2) * 1.
         if (irah LT 0 or irah GE 24 or iram LT 0 or iram GE 60 or iras LT 0. or iras GE 60.) then b
egin
            print,'Coordinate RA h/m/s value is invalid'
            print,'  You entered  : ', input
            print,'  Hour must be between 0 and 24, minute and second must be between 0 and 60'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of target loop
         endif
```

```
         irad = TEN(irah,iram,iras) * 15.  ; Convert from h:m:s to decimal degrees
;
;        Extract DEC and convert to decimal degrees
;
         work = strsplit(idc,':',/extract)
         nelem = size(work,/dimensions)
         If (nelem(0) NE 3) then begin    ; 3 elements not found (dcd, dcm, dcs)
            print,'Coordinate DEC format is invalid'
            print,'  You entered  : ', input
            print,'  Valid example: ', '07:01:38.10 +48:22:47.0 2000.0'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of target loop
         endif

         idcd = work(0) * 1
         idcm = work(1) * 1
         idcs = work(2) * 1.
         if (idcd LT -90 or idcd GE +90 or idcm LT 0 or idcm GE 60 or idcs LT 0. or idcs GE 60.) the
n begin
            print,'Coordinate DEC d/m/s value is invalid'
            print,'  You entered  : ', input
            print,'  Degree must be between -90 and +90, minute and second must be between 0 and 60'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of HD loop
         endif
         idecd = TEN(idcd,idcm,idcs) ; Convert from d:m:s to decimal degrees
;
;        Extract & validate epoch
;
         iepoc = iep * 1.
         if (iepoc LT 1950. or iepoc GT 2100.) then begin
            print,'Coordinate epoch value is invalid'
            print,'  You entered  : ', input
            print,'  Epoch must be between 1950.0 and 2100.0'
            print,'  This data line will be ignored'
            CONTINUE ; Skip to next iteration of target loop
         endif

     endelse


;
;  Save HD ID and coordinates of the target in array
;
      nbr_tar = nbr_tar + 1
      if (nbr_tar EQ 1) then begin
         inp_hda = curhd
         inp_raa = irad     ; RA in degrees
         inp_deca = idecd   ; HIP DEC in degrees
         inp_epocha = iepoc ; Epoch of HIP coordinates
      endif else begin
         inp_hda = [inp_hda, curhd]
         inp_raa = [inp_raa, irad]
         inp_deca = [inp_deca, idecd]
         inp_epocha = [inp_epocha, iepoc]
      endelse

endwhile  ; End of load HD loop

close,1  ; Close input file

if (nbr_tar EQ 0) then begin          ; No valid targets found
   print,'No valid targets found!'
   print,'  Please fix the input file and rerun this program'
   goto, done
endif


;##
;##   INPUT DATA HAS BEEN OBTAINED. NOW, START PROCESSING!
;##

openw,2,'./chara_planB.out'

;
;  Print parameters & headings
;
printf,2,'CHARA observing report created by CHARA_PLANB on ', SYSTIME()
printf,2,' '
```

```
pdate = string(format='(I4,"/",I2,"/",I2)', year_obs, month_obs, day_obs)
sub_string,pdate,' ','0'  ; Substitute blanks with zeroes
printf,2,format='("Observing Date: ",A10)', pdate
printf,2,format='("Wave Band: ",A1)', wave_band
printf,2,format='("Minimum observing time required per target: ",F5.2," hours")', min_obst
printf,2,format='("Total number of valid targets: ",I4)', nbr_tar
printf,2,' '
printf,2,'                                              Obs     Obs Window Opens     Obs Window Closes
 Max  at      Min  at    Max  at'
printf,2,' HD ID  <=== Coordinates ===>  Epoch    Dur     HA     UT    Alt     HA     UT    Alt
 Alt  UT     Base  UT   Base  UT'
printf,2,'                                              (h)     (h) (hh:mm) (deg)    (h) (hh:mm) (deg)
(deg)         (m)        (m)'
printf,2,' '
;
print,' '
print,format='("Total number of valid targets to process: ",I4)', nbr_tar
;
;  Process each baseline
;
for bli = 0, nbr_bl - 1 do begin

    tel_1 = inp_tel1a(bli)
    tel_2 = inp_tel2a(bli)
    curpops1 = inp_pop1a(bli,*)
    curpops2 = inp_pop2a(bli,*)

    print,' '
    print,'Processing baseline: ', tel_1, '-', tel_2, '  ...'

;
;   Process each POP combination
;
    for pop1i = 0, 4 do begin

       pop_1 = curpops1(pop1i)
       if (pop_1 EQ 0) then CONTINUE ; Skip zero POP

       for pop2i = 0, 4 do begin

          pop_2 = curpops2(pop2i)
          if (pop_2 EQ 0) then CONTINUE ; Skip zero POP

;
;         Process each target
;
;         Print start of Baseline/POP to file
          printf,2,format='("Baseline/POP: ",A2,"(",I1,")-",A2,"(",I1,")")', $
               tel_1, pop_1, tel_2, pop_2
          printf,2,' '

          obsct = 0
          for tari = 0, nbr_tar - 1 do begin

             ra = inp_raa(tari)
             dec = inp_deca(tari)
             epoch = inp_epocha(tari)

             chk_avail, tel_1, tel_2, pop_1, pop_2, ra, dec, epoch, $
                           str_obs_ha, end_obs_ha, str_obs_alt, end_obs_alt, $
                           str_obs_ut, end_obs_ut, min_pbase, min_pbase_ut, $
                           max_pbase, max_pbase_ut, max_alt, max_alt_ut, $
                           nbr_avl_int

             obsfl = 'N'
             for ri = 0, nbr_avl_int - 1 do begin ; process each avaliable interval

              obs_dur = end_obs_ha(ri) - str_obs_ha(ri)
              if (obs_dur GE min_obst) then begin
                obsfl = 'Y'
;
;            Format variables for printing
;
               if (inp_hda(tari) EQ 0.) then phd = ' ' $
               else phd = string(format='(I6)',inp_hda(tari))
               radec, ra, dec, ihr, imin, xsec, ideg, imn, xsc
               pra = string(format='(I2,":",I2,":",F4.1)',ihr,imin,xsec)
               sub_string,pra,' ','0'  ; Substitute blanks with zeroes
;              If deg is 0, and DEC is LT 0, radec returns ideg as 0 and sign with imn!
```

```
              if (ideg EQ 0 AND imn LT 0) then $
                 pdec = string(format='("-",I2,":",I2,":",F4.1)',ideg,abs(imn),xsc) $
              else $
                 pdec = string(format='(I3,":",I2,":",F4.1)',ideg,imn,xsc)
              if (strmid(pdec,0,2) EQ ' -') then pdec = '-0' + strmid(pdec,2,9)
              if (strmid(pdec,0,1) EQ ' ') then pdec = '+' + strmid(pdec,1,10)
              sub_string,pdec,' ','0'  ; Substitute blanks with zeroes
              hms = sixty(str_obs_ut(ri))
              pstr_obs_ut = string(format='(I2,":",I2)',hms(0),hms(1))
              sub_string,pstr_obs_ut,' ','0'  ; Substitute blanks with zeroes
              hms = sixty(end_obs_ut(ri))
              pend_obs_ut = string(format='(I2,":",I2)',hms(0),hms(1))
              sub_string,pend_obs_ut,' ','0'  ; Substitute blanks with zeroes
              hms = sixty(min_pbase_ut(ri))
              pmin_pbase_ut = string(format='(I2,":",I2)',hms(0),hms(1))
              sub_string,pmin_pbase_ut,' ','0'  ; Substitute blanks with zeroes
              hms = sixty(max_pbase_ut(ri))
              pmax_pbase_ut = string(format='(I2,":",I2)',hms(0),hms(1))
              sub_string,pmax_pbase_ut,' ','0'  ; Substitute blanks with zeroes
              hms = sixty(max_alt_ut(ri))
              pmax_alt_ut = string(format='(I2,":",I2)',hms(0),hms(1))
              sub_string,pmax_alt_ut,' ','0'  ; Substitute blanks with zeroes

              printf,2,format='(A6," ",A11,A12,F8.2,F6.2,F8.2,"  ",A5,F6.1,F8.2,"  ",A5, F6.1, F8.1
, " ", A5, I7," ",A5, I5," ",A5)', $
                 phd, pra, pdec, epoch, obs_dur, str_obs_ha(ri), pstr_obs_ut, $
                 str_obs_alt(ri), end_obs_ha(ri), pend_obs_ut, end_obs_alt(ri), $
                 max_alt(ri), pmax_alt_ut, $
                 min_pbase(ri), pmin_pbase_ut, max_pbase(ri), pmax_pbase_ut

             endif   ; end obs window avail

            endfor    ; end of interval loop

            if (obsfl EQ 'Y') then   obsct = obsct + 1

         endfor     ; end of HD loop

           printf,2,' '
           printf,2,format='(I4," objects observable for: ",A2,"(",I1,")-",A2,"(",I1,")")', $
                obsct, tel_1, pop_1, tel_2, pop_2
           printf,2,' '
           print,format='(I4," objects observable for: ",A2,"(",I1,")-",A2,"(",I1,")")', $
                obsct, tel_1, pop_1, tel_2, pop_2

       endfor ; end of POP 2 loop

   endfor ; end of POP 1 loop

endfor  ; end of baseline loop

close,2

;
;  Completion message
;
print,' '
print,'All done!  Look in ./chara_planB.out for results'

done:
return
end                ; End of chara_planB

;#####################################################################
; END PROGRAM: CHARA_PLAN_B                                          #
;#####################################################################


;#########################################################################
;#  CHECK_AVAIL                                                          #
;#                                                                       #
;#  An observing prepation tool for the CHARA array                      #
;#  Deepak Raghavan (raghavan@chara.gsu.edu)                             #
;#  Original Version: January 3, 2007                                    #
;#                                                                       #
;#  For a given observing date, filter, baselines, POPs, RA & DEC (in    #
;#  degrees) along with its equinox epoch (in Besselian Year) of target,#
;#  this program checks if the object is observable and returns the     #
;#  time-window of availablility, along with corresponding parameters   #
```

```
;#  such as hour angle, altitude, and projected baseline information.   #
;#  A target is considered observable at times between dusk and dawn    #
;#  when its altitude is greater than 30 degrees and delay is           #
;#  available within the maximum range to compensate for path length    #
;#  differences between the two telescopes.  Most of the logic in       #
;#  CHK_AVAIL was borrowed from Jason Aufdenbereg's CHARA_PLAN          #
;#  program, with modifications and enhancements as required.          #
;#                                                                      #
;#  Input: Tel_1, Tel_1, POP_1, POP_2, HDNUM                            #
;#  Common variables required: See common blocks below                  #
;#  Output: Nbr_Avl_Int: 0 if star is not available, else contains      #
;#                       the number of intervals avail for obs          #
;#            (e.g. is star is avail 01:30-02:45 and again 06:00-08:00, #
;#             this number will be 2)                                   #
;#          Start & End HA, Alt, and UT, Min & Max proj baseline        #
;#          with corresponding UT times,                                #
;#          all of which are arrays with Nbr_Avl_Int elements.          #
;#                                                                      #
;########################################################################
pro chk_avail, tel_1, tel_2, pop_1, pop_2, ra, dec, epoch, $
               str_obs_ha, end_obs_ha, str_obs_alt, end_obs_alt, $
               str_obs_ut, end_obs_ut, min_pbase, min_pbase_ut, $
               max_pbase, max_pbase_ut, max_alt, max_alt_ut, nbr_avl_int

;
;  Common variables between CHARA_PLAN and this procedure
;
common CHARA, TELESCOPES, BASELNAME, POPS
common params, year_obs, month_obs, day_obs, wave_band, min_obst

;#
;#  SETUP CHARA CONSTANTS
;#
;## THE CHARA CONSTANTS BELOW ARE FROM TELESCOPES.CHARA FILE OBTAINED FROM THEO ON 1/4/2007. DR
;
;  Delays for telescope and pop combinations (in meters)
;                         POP1             POP2            POP3            POP4            POP5
POP_DELAYS = dblarr(6,5)
POP_DELAYS(0,*)= [   0.000000000d0,  36.583816633d0, 73.152000000d0,109.743124329d0,143.089005503d0]
  ; S1
POP_DELAYS(1,*)= [ -36.576000000d0,   0.000000000d0, 36.576000000d0, 73.152000000d0,106.479000000d0]
  ; S2
POP_DELAYS(2,*)= [   0.000000000d0,  36.576000000d0, 73.101581148d0,109.686953167d0,142.999272291d0]
  ; E1
POP_DELAYS(3,*)= [ -73.125000000d0, -36.516000000d0,  0.000000000d0, 36.575000000d0, 69.986000000d0]
  ; E2
POP_DELAYS(4,*)= [ -73.116500000d0, -36.576000000d0,  0.000000000d0, 36.605196000d0, 69.903000000d0]
  ; W1
POP_DELAYS(5,*)= [-143.055000000d0,-106.479000000d0,-69.903000000d0,-33.327000000d0,  0.000000000d0]
  ; W2

;#
;# Differential Airpaths (relative to S1) in meters (note the divide
;  by 1.d6 at the end of the array to convert from microns to meters)
;#
AIRPATH = [0.d0, 4532654.762d0, 15314546.348d0, 26372594.395d0,$
           29129044.683d0, -8668143.182d0]/1.d6  ;S1,S2,E1,E2,W1,W2

OPLE_MAX=88 ; in meters  ; The full length of delay provided by the delay carts

;#
;# CHARA LATITUDE and LONGITUDE (for S1 from telescopes.chara)
;#
S1_LAT  = ten(34.,13.,27.7813d0)*(!pi/180.d0) ; lat. in deg --> radians
S1_LONG = ten(-118.,3.,25.31272d0)*(!pi/180.d0) ;long in deg --> radians

;
;#  X, Y, Z offset for each telescope relative to S1 in meters
;          S1       S2             E1               E2            W1                W2
;
XOFFSET=[0.0d0, -5748393.059d0, 125337986.867d0, 70389114.6d0,-175073611.569d0, -69080651.822d0]/1.d
6
YOFFSET=[0.0d0, 33581340.790d0, 305925736.557d0,269714608.0d0, 216338950.344d0, 199355622.792d0]/1.d
6
ZOFFSET=[0.0d0,   643880.188d0,  -5920522.324d0, -2802196.8d0, -10806621.168d0,    447470.433d0]/1.d
6

;  Non CHARA-related constants:
```

```
DOM = [31,28,31,30,31,30,31,31,30,31,30,31]  ; Days in each month (non-leap year)

;#
;#  SETUP VARIABLES BASED ON INPUT AND CONSTANTS
;#

;
;  Convert observing date to Besselian Year format
;
obs_dt_BY = year_obs
for i = 0,month_obs-2 do obs_dt_BY = obs_dt_BY + DOM(i) / 365.25 ; Add prior month days
obs_dt_BY = obs_dt_BY + day_obs / 365.25 ; Add current month days
if ((year_obs mod 4) EQ 0 AND (year_obs mod 400) NE 0 $
     AND month_obs GT 2) then obs_dt_BY = obs_DT_BY + 1/365.25  ; Account for leap year

;
;  Validate telescopes & baselines, flip telescope order if required
;
t1 = where(TELESCOPES EQ  tel_1) ; Set numeric value of Tel 1
if (t1(0) EQ -1) then begin   ; Invalid Tel 1
   print, "Invalid value for Telescope 1! ", tel_1
   return
endif
t2 = where(TELESCOPES EQ  tel_2) ; Set numeric value of Tel 1
if (t2(0) EQ -1) then begin   ; Invalid Tel 2
   print, "Invalid value for Telescope 2! ", tel_2
   return
endif

;  Find baseline number.  If the telescopes are in flipped order, flip
;  them back and flip the POPs as well.  (e.g. E1S1 should be switched
;  to S1E1

tcomb = tel_1 + tel_2
blnum = where(BASELNAME EQ tcomb) ; Set numeric value of baseline
if (blnum(0) EQ -1) then begin   ; Baseline not found
;  CHECK IF TELS ARE FLIPPED!
   tcomb = tel_2 + tel_1
   blnum = where(BASELNAME EQ tcomb) ; Set numeric value of baseline
   if (blnum(0) EQ -1) then begin   ; Invalid Baseline
      print, "Invalid baseline! ", tcomb
      return
   endif else begin  ; FLIP TELESCOPES TO RIGHT ORDER
      hold_tel = tel_1
      tel_1 = tel_2
      tel_2 = hold_tel
      hold_t = t1
      t1 = t2
      t2 = hold_t
      hold_pop = pop_1  ;  Flip pop when telescopes are flipped!
      pop_1 = pop_2
      pop_2 = hold_pop
   endelse
endif

;
;  Set pop numbers for telescopes 1 & 2
;
pop1 = where(POPS EQ pop_1)
if (pop1(0) EQ -1) then begin   ; Invalid Pop
   print, "Invalid POP for Tel 1! ", pop_1
   return
endif
pop2 = where(POPS EQ pop_2)
if (pop2(0) EQ -1) then begin   ; Invalid Pop
   print, "Invalid POP for Tel 2! ", pop_2
   return
endif

;
;  Compute delay for telescope & pop combination
;
pop_delay = POP_DELAYS(t2,pop2) - POP_DELAYS(t1,pop1)
pop_delay = pop_delay(0) ; Convert to scalar so future math with vectors works!

;
; precess to current epoch
;
wra  = ra
```

```
wdec = dec
precess,wra,wdec,epoch,obs_dt_BY
wra  = wra/15.0d0           ;RA:  degrees ---> hours
wdec = wdec*!pi/180.d0      ;DEC: degrees --->;radians

;#  Following code is largely lifted from CHARA_CONFIG proecdure in
;#  CHARA_PLAN and modified as needed to suit the needs of this
;#  program.  Deepak Raghavan 2007/01/02

;#
;# Return air path difference (in meters) for current baseline

basevec=dblarr(3)
basevec(0) = xoffset(t1) - xoffset(t2) ;east
basevec(1) = yoffset(t1) - yoffset(t2) ;north
basevec(2) = zoffset(t1) - zoffset(t2) ;up
air_diff = AIRPATH(t1) - AIRPATH(t2)
air_diff = air_diff(0) ; Convert to scalar so future math with vectors works!


;#
;# from the WAVEBAND user input, select K or H band
;#

if (wave_band eq 'K') then lam = 2.2*1.e-6  ; wavelength in meters
if (wave_band eq 'H') then lam = 1.6*1.e-6  ; wavelength in meters


;##################################################################################
;# Compute local mean sidereal time for a given date                              #
;##################################################################################
;# We need this to convert hour angles to UT times for a given date
;#
;#  See "Greenwich Mean Sidereal Time GMST" (on Page B6 from the Astronomical Almanac)
;#  under TIME-SCALES: "Relationships between universal and sidereal time"
;#
;# use ASTROLIB idl routine 'juldate' to compute the reduced julian
;# date (RJD)at UT=0h for the users inputs YEAR, MONTH, DAY
;#

juldate,[year_obs,month_obs,day_obs,0,0,0],rjd  ; Zeroes for time

;#
;# Here we follow the Astronomical Almanac Formulae
;# Also see http://aa.usno.navy.mil/faq/docs/GAST.html

tu=(rjd-51545.d0)/36525.d0  ;# Julian centuries of 36525 days since ;J2000.0

;# Greenwich Mean Sidereal Time at Oh UT (in seconds)
gmst= 24110.54841d0 + (8640184.812866d0*tu) + (0.093104d0*tu*tu) + (6.2d-6*tu*tu*tu)

;# Greenwich Mean Sidereal Time in hours
;#
gmst_h=(gmst/3600.d0)
while(gmst_h gt 24) do     gmst_h=gmst_h-24.d0 ; Reduce value to between 0 - 24
while(gmst_h lt 0) do     gmst_h=gmst_h+24.d0

;#
;# Local Mean Sidereal Time in hours at 0h UT (longitude correction)
;#
lmst_h=(gmst/3600.d0)+((S1_LONG*180./!pi)/15.d0)
while(lmst_h gt 24) do lmst_h=lmst_h-24.d0 ; Reduce value to between 0 - 24
while(lmst_h lt 0) do lmst_h=lmst_h+24.d0

;# Compute the hour angle of the target star at Oh UT
;# We use this to compute the UT times which correspond the vector
;# of hour angles constructed below

ha_at_ut_zero=lmst_h-ra  ;HA of star at 0h UT on RJD

;################################################################################
; end time calcucations
;################################################################################


;################################################################################
; Setup vectors to collect informatoin such as UT time, Altitude etc
; for hour angle between -6h and +6h
;################################################################################
```

```
mm = 48 ; Size of arrays, one element per 15 minutes

pbasevec=dblarr(mm+1)           ;vector to save projected baselines (in meters)
havec=dblarr(mm+1)              ;vector to save hour angles (in hours)
altvec=dblarr(mm+1)             ;vector to save altitudes   (in degrees)
azvec=dblarr(mm+1)              ;vector to save azimuths    (in degrees)
u_vec=dblarr(mm+1)              ;vector of save U component of spatial frequency (cycles/arcsec)
v_vec=dblarr(mm+1)              ;vector of save V component of spatial frequency (cycles/arcsec)
sfvec=dblarr(mm+1)              ;vector to save spatial frequenices sf = sqrt(u^2 + v^2) (cycles/arc
sec)
pavec=dblarr(mm+1)              ;vector of save position angles (degrees). note: PA=arctangent(U/V)
gdvec=dblarr(mm+1)              ;vector of geometric delays (in meters)


;#
;#  TOP of Hour Angle loop.
;#
for m=0,mm do begin

;#  compute hour angle (in radians)
;#  from m=0,48, ha goes from -6 h to +6 h, one point every 15 minutes.
;#
    ha=(0.25*m-6)*(15.d0*!pi/180.d0) ; hour angle in hours --> radians

;#
;# Compute Altitude at this hour angle (see Page B61, Astrononmical Almanac)
;#
    sin_altitude=sin(wdec)*sin(S1_LAT)+cos(wdec)*cos(ha)*cos(S1_LAT)
    altitude=asin(sin_altitude)*180./!pi ;altitude in degress

;#
;# Compute Azimuth at this hour angle (see Page B61, Astrononmical Almanac)
;#
    sin_azimuth=-1.d0*cos(wdec)*sin(ha)/cos(asin(sin_altitude))
    cos_azimuth= sin(wdec)*cos(S1_LAT)-cos(wdec)*cos(ha)*sin(S1_LAT)
;#
;#  pick the right quadrant for the azimuth!
;#  also convert to degrees from radians
;#
    if(cos_azimuth ge 0 and sin_azimuth ge 0) then azimuth=asin(sin_azimuth)*180./!pi       ;1st Q
    if(cos_azimuth le 0 and sin_azimuth ge 0) then azimuth=180.0-asin(sin_azimuth)*180./!pi ;2nd Q
    if(cos_azimuth le 0 and sin_azimuth le 0) then azimuth=180.0-asin(sin_azimuth)*180./!pi ;3rd Q
    if(cos_azimuth ge 0 and sin_azimuth le 0) then azimuth=360+asin(sin_azimuth)*180./!pi   ;4th Q

;#
;# Compute U,V coordinates for this Hour Angle
;# Mel Dyck's talk  "Interferometry with Two Telescopes" in
;# Principles of Long Baseline Stellar Interferometry (equation 12.1, page 189)
;# both u and v are in cycles/arcsecond
;#

;# U
    u=(basevec(0)*cos(ha) - basevec(1)*sin(S1_LAT)*sin(ha) +$
       basevec(2)*cos(S1_LAT)*sin(ha) )/(206265.*lam)
;# V
    v=(basevec(0)*sin(wdec)*sin(ha) + $
       basevec(1)*(sin(S1_LAT)*sin(wdec)*cos(ha) + cos(S1_LAT)*cos(wdec)) -$
       basevec(2)*(cos(S1_LAT)*sin(wdec)*cos(ha) - sin(S1_LAT)*cos(wdec)))/(206265.*lam)

;#  gdelay =  delay (in meters) for a baseline vector with north,
;# east  (and now north earth and "up") components.  A star in the west will
;# have a positive delay, while a star in the east will be negative delay.
;#
    gdelay= - basevec(0)*cos(wdec)*sin(ha) - $
     basevec(1)*(sin(S1_LAT)*cos(wdec)*cos(ha) - cos(S1_LAT)*sin(wdec))  +$
     basevec(2)*(cos(S1_LAT)*cos(wdec)*cos(ha) + sin(S1_LAT)*sin(wdec))

;#
;# spatial frequency for a symmetric source
;#
    sf=sqrt(u^2 + v^2)

;#
;# projected baseline (in meters)
;#
    pbase=sf*206265.*lam

;#
```

```
;# Position angle (East of North)
;#
    pa=atan(u/v)*180./!pi
;#
;# It's nice to keep the position angle between -60 to 120
;# since the position angle of the projected baseline is same when
;# rotated 180 degrees
;#
;#
    if (pa le -60) then pa=pa+180

;#
;# Save values at this hour angle step into vectors
;#

    havec(m)=ha*180./(!pi*15.)  ;hour angle [in hours]
    u_vec(m)=u                  ;U [in cycles/arcsec]
    v_vec(m)=v                  ;V [in cycles/arcsec]
    sfvec(m)=sf                 ;spatial frequency [in cycles/arcsec]
    pbasevec(m)=pbase           ;projected baselines [in meters]
    pavec(m)=pa                 ;position angle [in degrees]
    altvec(m)=altitude          ;altitude [in degrees]
    azvec(m)=azimuth            ;azimuth [in degrees]
    gdvec(m)=gdelay             ;geometric delay [in meters]

;# BOTTOM of hour angle loop
endfor

;
;#  Compute UT Time corresponding to hour angle
;
gmstvec = havec + wra - ((S1_LONG*180./!pi)/15.d0)
uttime  = (gmstvec-gmst_h)/1.002737


;
;# OPLE Cart Delay Computation
;
;# This will be used to check the times during which the delay carts
;# can move within the possible range to compensate for path length
;# differences for the given baseline, POP, and target

;# the needed delay to be provided by the carts
cart_delay=-0.5*(gdvec-air_diff+pop_delay)

;#
;# Compute dusk and dawn times in terms of LMST and HA
;#
sunpos,rjd,S1_LAT,S1_LONG,tw_dusk,tw_dawn,lmst_dusk,lmst_dawn

ha_dusk = lmst_dusk - wra
ha_dawn = lmst_dawn - wra

if (ha_dawn lt -12) then ha_dawn=ha_dawn+24
if (ha_dawn gt 12) then ha_dawn=ha_dawn-24

if (ha_dusk lt -12) then ha_dusk=ha_dusk+24
if (ha_dusk gt 12) then ha_dusk=ha_dusk-24

;#
;#  Compute indices for which:
;#  ==>  Altitude is greater than 30 degrees (goodalti)
;#  ==>  Cart delay is within maximum limits (gooddelayi)
;#  ==>  Time corresponds to night-time (nighti)
;#  ==>  Satisfies all the above conditions (obsi)
;#
goodalti = where(altvec GT 30.)
gooddelayi = where(cart_delay LE OPLE_MAX/2.0 AND $
                   cart_delay GE -OPLE_MAX/2.d0)
if (ha_dawn GT ha_dusk) then $  ; Dawn time after Dusk
   nighti = where(havec GT ha_dusk AND havec LT ha_dawn) $ ; night = between dusk & dawn
else $                          ; Dusk time after Dawn
   nighti = where(havec GT ha_dusk OR havec LT ha_dawn)    ; night = before dawn or after dusk
;  Same conditions as above for night time are checked below
obsi = where(altvec GT 30. AND $
                    cart_delay LE OPLE_MAX/2.0 AND $
                    cart_delay GE -OPLE_MAX/2.d0 AND $
                    ((ha_dawn GT ha_dusk AND $
                    havec GT ha_dusk AND havec LT ha_dawn) $
```

```
                    OR (ha_dawn LE ha_dusk AND $
                    (havec GT ha_dusk OR havec LT ha_dawn))))

;#  Initialize return parameters

nbr_avl_int = 0
str_obs_ha = 0.
end_obs_ha = 0.
str_obs_alt = 0.
end_obs_alt = 0.
str_obs_ut = 0.
end_obs_ut = 0.
min_pbase = 0.
min_pbase_ut = 0.
max_pbase = 0.
max_pbase_ut = 0.
max_alt = 0.
max_alt_ut = 0.

if (obsi(0) EQ -1) then return  ; Star is not observable at all

;#  Separate out the non-consecutive availability
;#  e.g. if obsi = [4,5,6,7,13,14,15,16,17], set
;#  nbr_avl_int = 2, and
;#  obsi = [[4,5,6],[13,14,15,16,17]]  (2-D array)
t0obsi = obsi
t1obsi = [t0obsi(0)-1,t0obsi]  ; offset array by one element to right
t2obsi = t0obsi - t1obsi
brki = where(t2obsi NE 1)
if (brki(0) EQ -1) then nbr_avl_int = 1 $
else begin
   nbr_avl_int = SIZE(brki,/dimensions)
   nbr_avl_int = nbr_avl_int(0) + 1  ; convert to scalar, add 1
endelse

nt0 = size(t0obsi,/dimensions)
obsi = intarr(nbr_avl_int, nt0)  ; set up obsi as 2-D array of max possible size
obsi = obsi - 1 ; set initial values as -1 (invalid index)
; add element at begining as start of first interval, and at end out to size of array
if (nbr_avl_int EQ 1) then brki = [0, nt0] $
else brki = [0, brki, nt0]

for ti = 0, nbr_avl_int - 1 do begin    ; process each interval
    obsi(ti, 0:(brki(ti+1)-brki(ti)-1)) = t0obsi(brki(ti) : brki(ti+1)-1)
endfor
;##  End of logic to split obsi into arrays of consecutive availabilities!!

str_obs_ha   = fltarr(nbr_avl_int)
end_obs_ha   = fltarr(nbr_avl_int)
str_obs_alt  = fltarr(nbr_avl_int)
end_obs_alt  = fltarr(nbr_avl_int)
str_obs_ut   = fltarr(nbr_avl_int)
end_obs_ut   = fltarr(nbr_avl_int)
min_pbase    = fltarr(nbr_avl_int)
min_pbase_ut = fltarr(nbr_avl_int)
max_pbase    = fltarr(nbr_avl_int)
max_pbase_ut = fltarr(nbr_avl_int)
max_alt      = fltarr(nbr_avl_int)
max_alt_ut   = fltarr(nbr_avl_int)

for ti = 0, nbr_avl_int - 1 do begin ; Return data for each interval
    datai = where(obsi(ti, *) NE -1)
    cobsi = obsi(ti, datai)  ; Current observal indices
    str_obs_ha(ti) = MIN(havec(cobsi), str_obs_i)
    end_obs_ha(ti) = MAX(havec(cobsi), end_obs_i)
    str_obs_i = cobsi(str_obs_i)  ; Get to index of full vector!
    end_obs_i = cobsi(end_obs_i)  ; Get to index of full vector!
    str_obs_alt(ti) = altvec(str_obs_i)
    end_obs_alt(ti) = altvec(end_obs_i)
    str_obs_ut(ti) = uttime(str_obs_i)
    end_obs_ut(ti) = uttime(end_obs_i)
    min_pbase(ti) = MIN(pbasevec(cobsi), min_pbi)
    max_pbase(ti) = MAX(pbasevec(cobsi), max_pbi)
    max_alt(ti) = MAX(altvec(cobsi), max_alti)
    min_pbi = cobsi(min_pbi)  ; Get to index of full vector!
    max_pbi = cobsi(max_pbi)  ; Get to index of full vector!
    max_alti = cobsi(max_alti)  ; Get to index of full vector!
    min_pbase_ut(ti) = uttime(min_pbi)
    max_pbase_ut(ti) = uttime(max_pbi)
```

```
    max_alt_ut(ti) = uttime(max_alti)
endfor

return
end         ; End CHK_AVAIL

;#####################################################################
; END PROGRAM: CHK_AVAIL                                             #
;#####################################################################


;#####################################################################
; PROGRAM: RMV_BLANK                                                 #
;  Eliminate leading, trailing and embedded blanks from a string    #
;  Input: inp_out : The input string                                 #
;  Output: inp_out: The output string with blanks removed            #
;#####################################################################

pro rmv_blank, inp_out

arrsp = strsplit(inp_out,' ',/EXTRACT)
arrsz = size(arrsp,/dimensions)
inp_out = ''
for i = 0, arrsz(0)-1 do inp_out=inp_out+arrsp(i)

return
end

;#####################################################################
; PROGRAM: SUB_STRING                                                #
;  Substitute every occurance of a value with a substitute value    #
;  in a given string                                                 #
;  Input: inp_out : The input string                                 #
;  Input: old_byte: Byte to be substituted (string of length 1)     #
;  Input: new_byte: Substitution value (string of length 1)         #
;  Output: inp_out: The output string with substitutions made       #
;#####################################################################

pro sub_string, inp_out, old_byte, new_byte

len = strlen(inp_out)
new_str = inp_out
for i = 0, len-1 do begin
    if (strmid(inp_out, i, 1) EQ strmid(old_byte,0,1)) then $
       new_str = strmid(new_str, 0, i) + strmid(new_byte,0,1) + $
                 strmid(new_str, i+1, len-i-1)
endfor
inp_out = new_str

return
end

;#####################################################################
; END PROGRAM: SUB_STRING                                            #
;#####################################################################

;#####################################################################
; PROGRAM: PRECESS                                                   #
; Taken directly from CHARA_PLAN. No modifications made DR 1/4/07   #
;#####################################################################

pro precess, ra, dec, equinox1, equinox2, PRINT = print, FK4 = FK4, $
        RADIAN=radian
;+
; NAME:
;       PRECESS
; PURPOSE:
;       Precess coordinates from EQUINOX1 to EQUINOX2.
; EXPLANATION:
;       For interactive display, one can use the procedure ASTRO which calls
;       PRECESS or use the /PRINT keyword.   The default (RA,DEC) system is
;       FK5 based on epoch J2000.0 but FK4 based on B1950.0 is available via
;       the /FK4 keyword.
;
; CALLING SEQUENCE:
;       PRECESS, ra, dec, [ equinox1, equinox2, /PRINT, /FK4, /RADIAN ]
;
; INPUT - OUTPUT:
;       RA - Input right ascension (scalar or vector) in DEGREES, unless the
```

```
;               /RADIAN keyword is set
;       DEC - Input declination in DEGREES (scalar or vector), unless the
;               /RADIAN keyword is set
;
;       The input RA and DEC are modified by PRECESS to give the
;       values after precession.
;
; OPTIONAL INPUTS:
;       EQUINOX1 - Original equinox of coordinates, numeric scalar.  If
;               omitted, then PRECESS will query for EQUINOX1 and EQUINOX2.
;       EQUINOX2 - Equinox of precessed coordinates.
;
; OPTIONAL INPUT KEYWORDS:
;       PRINT - If this keyword is set and non-zero, then the precessed
;               coordinates are displayed at the terminal.    Cannot be used
;               with the /RADIAN keyword
;       FK4   - If this keyword is set, the FK4 (B1950.0) system
;               will be used otherwise FK5 (J2000.0) will be used instead.
;       RADIAN - If this keyword is set and non-zero, then the input and
;               output RA and DEC vectors are in radians rather than degrees
;
; RESTRICTIONS:
;       Accuracy of precession decreases for declination values near 90
;       degrees.  PRECESS should not be used more than 2.5 centuries from
;       2000 on the FK5 system (1950.0 on the FK4 system).
;
; EXAMPLES:
;       (1) The Pole Star has J2000.0 coordinates (2h, 31m, 46.3s,
;               89d 15' 50.6"); compute its coordinates at J1985.0
;
;       IDL> precess, ten(2,31,46.3)*15, ten(89,15,50.6), 2000, 1985, /PRINT
;
;               ====> 2h 16m 22.73s, 89d 11' 47.3"
;
;       (2) Precess the B1950 coordinates of Eps Ind (RA = 21h 59m,33.053s,
;       DEC = (-56d, 59', 33.053") to equinox B1975.
;
;       IDL> ra = ten(21, 59, 33.053)*15
;       IDL> dec = ten(-56, 59, 33.053)
;       IDL> precess, ra, dec ,1950, 1975, /fk4
;
; PROCEDURE:
;       Algorithm from Computational Spherical Astronomy by Taff (1983),
;       p. 24. (FK4). FK5 constants from "Astronomical Almanac Explanatory
;       Supplement 1992, page 104 Table 3.211.1.
;
; PROCEDURE CALLED:
;       Function PREMAT - computes precession matrix
;
; REVISION HISTORY
;       Written, Wayne Landsman, STI Corporation  August 1986
;       Correct negative output RA values   February 1989
;       Added /PRINT keyword      W. Landsman   November, 1991
;       Provided FK5 (J2000.0)  I. Freedman   January 1994
;       Precession Matrix computation now in PREMAT   W. Landsman June 1994
;       Added /RADIAN keyword                         W. Landsman June 1997
;       Converted to IDL V5.0   W. Landsman   September 1997
;-
  On_error,2                                          ;Return to caller

  npar = N_params()
  deg_to_rad = !DPI/180.0D0

   if ( npar LT 2 ) then begin

     print,'Syntax - PRECESS, ra, dec, [ equinox1, equinox2,' + $
                ' /PRINT, /FK4, /RADIAN ]'
     print,'         NOTE: RA and DEC must be in DEGREES unless /RADIAN is set'
     return

  endif else if (npar LT 4) then $
      read,'Enter original and new equinox of coordinates: ',equinox1,equinox2

  npts = min( [N_elements(ra), N_elements(dec)] )
  if npts EQ 0 then $
       message,'ERROR - Input RA and DEC must be vectors or scalars'

  if not keyword_set( RADIAN) then begin
          ra_rad = ra*deg_to_rad     ;Convert to double precision if not already
```

```
         dec_rad = dec*deg_to_rad
  endif else begin
        ra_rad= double(ra) & dec_rad = double(dec)
  endelse

  a = cos( dec_rad )

 CASE npts of                    ;Is RA a vector or scalar?

   1:    x = [a*cos(ra_rad), a*sin(ra_rad), sin(dec_rad)] ;input direction

   else: begin

         x = dblarr(npts,3)
         x[0,0] = a*cos(ra_rad)
         x[0,1] = a*sin(ra_rad)
         x[0,2] = sin(dec_rad)
         x = transpose(x)
         end

   ENDCASE

   sec_to_rad = deg_to_rad/3600.d0

; Use PREMAT function to get precession matrix from Equinox1 to Equinox2

  r = premat(equinox1, equinox2, FK4 = fk4)

  x2 = r#x      ;rotate to get output direction cosines

 if npts EQ 1 then begin                 ;Scalar

        ra_rad = atan(x2[1],x2[0])
        dec_rad = asin(x2[2])

 endif else begin                ;Vector

        ra_rad = dblarr(npts) + atan(x2[1,*],x2[0,*])
        dec_rad = dblarr(npts) + asin(x2[2,*])

 endelse

  if not keyword_set(RADIAN) then begin
        ra = ra_rad/deg_to_rad
        ra = ra + (ra LT 0.)*360.D            ;RA between 0 and 360 degrees
        dec = dec_rad/deg_to_rad
  endif else begin
        ra = ra_rad & dec = dec_rad
  endelse

  if keyword_set( PRINT ) then $
      print, 'Equinox (' + strtrim(equinox2,2) + '): ',adstring(ra,dec,1)

  return
end

;#####################################################################
; END PROGRAM: PRECESS                                               #
;#####################################################################

;#####################################################################
; PROGRAM PROGRAM: SUNPOS                                            #
; Taken directly from CHARA_PLAN. No modifications made DR 1/4/07   #
;#####################################################################
;+
; NAME: sunpos
;
;
;
; PURPOSE: compute the position of the sun and return times (UT)
;          for astronomical twilight (both dusk and dawn) & LSMT times too.
;
;"Low precision formulas for the Sun's coordinates and the equation of time"
;From Astronomical Almanac (1989) page C24

;
; CALLING SEQUENCE:
;          sunpos,JD_IN,LAT,LONG,TW_DUSK,TW_DAWN,LMST_DUSK,LMST_DAWN
;
```

```
;
; INPUTS:
;          JD_IN = reduced julian date
;
;          LAT = latitude in radians
;
;          LONG = longitude in radians
;
;
; OPTIONAL INPUTS: none

;
;
; KEYWORD PARAMETERS: none
;
;
; OUTPUTS:

;          TW_DUSK = UT time of dusk (astronomical twilght) after sunset
;                    when zenith distance of the sun is at 120 degrees
;
;          TW_DAWN = UT time of dawn (astronomical twilght) before sunrise
;                    when zenith distance of the sun is at 120 degrees
;
;          LMST_DUSK = Local Mean Sideral Time of dusk
;                    (astronomical twilght: after sunset when zenith
;                    distance of the sun is at 120 degrees)
;
;          LMST_DAWN = Local Mean Sideral Time of dawn
;                    (astronomical twilght: before sunrise when zenith
;                    distance of the sun is at 120 degrees);
;
;
; OPTIONAL OUTPUTS: none
;
;
;
; COMMON BLOCKS: none
;
;
;
; SIDE EFFECTS: none
;
;
;
; RESTRICTIONS: This will probably break if choose the LAT and LONG
;               near or above/below the artic/anarctic circles!
;
; EXAMPLE:
;
;     At CHARA,  25-DEC-1981
;
;   sunpos,44963.5d0, ten(34.,13.,0.)*(!pi/180.d0),$
;        ten(-118.,03.,36.)*(!pi/180.d0),tw_dusk,tw_dawn,lmst_dusk,lmst_dawn
;
;   print,tw_dusk,tw_dawn
;   3.2904176       12.416673
;
;
; MODIFICATION HISTORY:
;
; comments added/improved: 13/feb/04 (jpa)
;
; first version early December 2003 (jpa)
;
;-

pro sunpos,jd_in,lat,long,tw_dusk,tw_dawn,lmst_dusk,lmst_dawn

n_points=96

;intialize vectors
altsun=fltarr(n_points) ;altitude of the sun
time=fltarr(n_points)   ;time in hours
stime=fltarr(n_points)  ;
ra_vec=fltarr(n_points)
ra_h_vec=fltarr(n_points)
dec_vec=fltarr(n_points)
ha_vec=fltarr(n_points)
```

```
lmst_vec=fltarr(n_points)
l_vec=fltarr(n_points)
g_vec=fltarr(n_points)
lambda_vec=fltarr(n_points)

for jj=0,n_points-1 do begin

    hour=jj/4.d0        ;hours run from 0 h to 23.75 h in 0.25 h steps

;    jd=jd_in+0.5+(hour/24.d0)   ;compute RJD for each hour step why
;    the did I add 0.5 here?? looks like a bug to me!

    jd=jd_in+(hour/24.d0)   ;compute RJD for each hour step

;from Almanac formulae
    n=jd-51545.d0

;Mean longitude of Sun, corrected for aberration
    L=280.460d0 + (0.9856474d0*n)

;Mean anomaly
    g=357.528d0 + (0.9856003d0*n)

;put L and g in the range 0 to 360 degrees by adding multiples of 360

    while (L gt 360.d0) do L=L-360.d0
    while (g gt 360.d0) do g=g-360.d0

;Ecliptic longitude
    lambda=L+(1.915d0 * sin(!pi*g/180.d0)) + (0.020 * sin (!pi*2.d0*g/180.d0))

    while (lambda lt 0.d0) do lambda=lambda+360.d0
    while (lambda gt 360.d0) do lambda=lambda-360.d0

;# Obliquity of ecliptic
    epsilon=23.439 - (0.0000004d0*n)

;# right ascension of the ran
    ra=atan(cos(epsilon*!pi/180.d0)*tan(lambda*!pi/180.d0))

    ra_deg=ra*180.d0/!pi

;# R.A. should be in the same quadrant as lambda, but the arctan
;# expression containing the obliquity of the ecliptic may place
;# the R.A. 90 degrees off. adjust R.A. accordingly
;
;# We do this because the R.A. will be discontinuous across lambda
;# quadrants otherwise
;#

    if (lambda ge 0.d0 and lambda le 90.d0) then begin
        while (ra_deg lt 0.d0)  do ra_deg=ra_deg+90
        while (ra_deg gt 90.d0)  do ra_deg=ra_deg-90
    endif

    if (lambda gt 90.d0 and lambda le 180.d0) then begin
        while (ra_deg lt 90.d0)  do ra_deg=ra_deg+90
        while (ra_deg gt 180.d0)  do ra_deg=ra_deg-90
    endif

    if (lambda gt 180.d0 and lambda le 270.d0) then begin
        while (ra_deg lt 180.d0)  do ra_deg=ra_deg+90
        while (ra_deg gt 270.d0)  do ra_deg=ra_deg-90
    endif

    if (lambda gt 270.d0 and lambda le 360.d0) then begin
        while (ra_deg lt 270.d0)  do ra_deg=ra_deg+90
        while (ra_deg gt 360.d0)  do ra_deg=ra_deg-90
    endif

;#RA  of the sun in hours
    ra_h=ra_deg/15.d0

;# RA of the sun in radians
    ra=ra_h*15.d0*!pi/180.d0

;# Declination of the sun in radians
    dec=asin(sin(epsilon*!pi/180.d0)*sin(lambda*!pi/180.d0))
```

```
;# See  GMST (Page B6 from the Astronomical Almanac)
;# TIME-SCALES: "Relationships between universal and sidereal time"

;with reduced JD
    tu=(jd-51545.d0)/36525.d0 ;Julian centuries of 36525 days since ;J2000.0

;# GMST in seconds at 0h UT
    gmst= 24110.54841d0 + (8640184.812866d0*tu) + (0.093104d0*tu*tu) + (6.2d-6*tu*tu*tu)

;Greenwich mean sidereal time in hours
    gmst_h=(gmst/3600.d0)+ (hour*1.00273791d0)

    while(gmst_h gt 24) do gmst_h=gmst_h-24.d0 ;
    while(gmst_h lt 0) do gmst_h=gmst_h+24.d0 ;

;# LMST: local mean sidereal time in hours
    lmst_h=(gmst/3600.d0)+ (hour*1.00273791d0)+long*(180./!pi)/15.d0

;# H.A. of the sun
    ha_h=lmst_h-ra_h

;# H.A. in radians
    ha_rad=(ha_h*15.d0)*!pi/180.d0

;#
;# compute solar altitude
;#
    sin_altitude=sin(dec)*sin(lat)+cos(dec)*cos(ha_rad)*cos(lat)
    altitude=asin(sin_altitude)*180./!pi ;in degrees

;# save variables into vectors at each time step

    altsun(jj)=altitude
    time(jj)=hour
    stime(jj)=lmst_h
    ra_vec(jj) = ra
    ra_h_vec(jj) = ra_h
    dec_vec(jj) = dec*180.d0/!pi
    ha_vec(jj) = ha_h
    lmst_vec(jj) = lmst_h
    L_vec(jj) = L
    g_vec(jj) = g
    lambda_vec(jj) = lambda

endfor

;#
;# zenith distance of the sun in degrees
;#
zd=90.d0-altsun

;#
;# UT of astronomical twilight
;#

k=where(zd ge 108.d0) ; for all zd > 108 degrees = astronomical twilight
j=sort(zd(k))

if (zd(k(j(0))) lt zd(k(j(0))+1)) then begin
;zd is increasing with time so this is dusk
    tw_dusk=interpol(time(k(j(0))-1:k(j(0))),zd(k(j(0))-1:k(j(0))),108.d0)
endif else begin
    tw_dawn=interpol(time(k(j(0)):k(j(0))+1),zd(k(j(0)):k(j(0))+1),108.d0)
endelse

if (zd(k(j(1))) lt zd(k(j(1))+1)) then begin
;zd is increasing with time so this is dusk
    tw_dusk=interpol(time(k(j(1))-1:k(j(1))),zd(k(j(1))-1:k(j(1))),108.d0)
endif else begin
    tw_dawn=interpol(time(k(j(1)):k(j(1))+1),zd(k(j(1)):k(j(1))+1),108.d0)
endelse


;local mean sidereal time of dusk and dawn (in hours)
lmst_dusk=(gmst/3600.d0)+ (tw_dusk*1.00273791d0)+long*(180./!pi)/15.d0
lmst_dawn=(gmst/3600.d0)+ (tw_dawn*1.00273791d0)+long*(180./!pi)/15.d0

while(lmst_dawn gt 24) do lmst_dawn=lmst_dawn-24.d0 ;
while(lmst_dawn lt 0) do lmst_dawn=lmst_dawn+24.d0 ;
```

```
while(lmst_dusk gt 24) do lmst_dusk=lmst_dusk-24.d0 ;
while(lmst_dusk lt 0) do lmst_dusk=lmst_dusk+24.d0 ;


end

;#####################################################################
; END PROGRAM: SUNPOS                                                 #
;#####################################################################
```

C.2 Example Output File

```
CHARA observing report created by CHARA_PLANB on Mon Jan 29 16:13:49 2007

Observing Date: 2007/01/21
Wave Band: K
Minimum observing time required per target:  1.50 hours
Total number of valid targets:  138

                                        Obs     Obs Window Opens     Obs Window Closes    Min  at    Max  at
 HD ID  <=== Coordinates ===>  Epoch    Dur     HA     UT    Alt     HA     UT    Alt    Base  UT   Base  UT
                                        (h)     (h) (hh:mm) (deg)    (h) (hh:mm) (deg)    (m)         (m)

Baseline/POP: S1(1)-E1(1)

 10086  01:39:35.8 +45:52:42.0 1991.25  4.00    1.25  02:47  71.5    5.25  06:46  31.1    323 06:46  329 03:47
 12051  01:59:06.5 +33:12:37.9 1991.25  3.75    1.00  02:51  77.5    4.75  06:36  32.1    327 04:06  330 06:36
 19373  03:09:02.9 +49:36:48.6 1991.25  5.50   -0.25  02:47  74.3    5.25  08:16  32.2    318 08:16  326 05:16
 20675  03:21:52.4 +49:04:15.8 1991.25  5.75   -0.50  02:44  74.1    5.25  08:28  32.1    319 08:28  327 05:29
140775  15:45:23.5 +05:26:50.4 1991.25  1.50   -3.75  11:51  30.7   -2.25  13:21  47.5    326 13:21  330 12:21
141795  15:50:48.9 +04:28:39.3 1991.25  1.50   -3.75  11:56  30.1   -2.25  13:26  46.8    325 13:26  330 12:26
142860  15:56:27.0 +15:39:53.0 1991.25  1.75   -4.25  11:32  30.2   -2.50  13:17  51.6    315 11:32  330 13:17
139225  15:36:29.2 +16:07:08.8 1991.25  2.25   -4.25  11:12  30.5   -2.00  13:27  57.5    314 11:12  330 13:12
142860  15:56:27.0 +15:39:53.0 1991.25  1.75   -4.25  11:32  30.2   -2.50  13:17  51.6    315 11:32  330 13:17

   9 objects observable for: S1(1)-E1(1)
```

C.3 SFP Detection

```
pro SFPF, inp_fil, inp_dir, DEBUG=debug, OUTF=outf, DISSERT=dissert

;***************************************************************************
;  CHARA Data Reduction  - Separated Fringe Packet Analysis               *
;                                                                          *
;  Analyze data from CHARA CLASSIC for separated fringe packet binaies.    *
;  NOTE: THIS VERSION USES THE FITS FILES GENERATED BY THE CHARA           *
;        SOFTWARE STARTING 2008 JAN.                                       *
;        For the old IRBRIEF format, see SFPbinary.pro                     *
;                                                                          *
;  Input:  Input File name to reduce (with wildcards)                      *
;          Input Directory name (default value assumed if not specified)   *
;          /DEBUG = Runs in debug mode, stops execution for reviews        *
;          /OUTF = Write output to file                                    *
;          /DISSERT = Suppress individual plots generated for /OUTF        *
;          but generate summary plot for each observation for dissertation.*
;  Input file contains:                                                    *
;          Output of "irbrief" run on Michelson, which creates a text      *
;          file with 3 arrays: Dither mirror position (microns), I_A,      *
;          and I_B - which are the measured intensities on A and B side    *
;          of beam combiner.                                               *
;  Output: Sumamry and detailed plot to help identify a secondary fringe,  *
;          if present.                                                     *
;                                                                          *
;  Original Version: Deepak Raghavan    March 26, 2007                     *
;                                                                          *
;  Modifications:                                                          *
;                                                                          *
;     5/21/2007  DR  Added average PS plot for display                     *
;                                                                          *
;                                                                          *
;***************************************************************************


;
;  Check input parameters
;
if (N_PARAMS() EQ 0) then begin
   print, 'Usage: SFPB, inp_fil, inp_dir, /debug'
   print, '/debug is optional, but input file (with wild-cards) is required'
   print, 'if inp_dir is not specified, the default value is used.'
   return
endif

;
;  Define constants
;

DEF_INP_DIR = '~/chara/sfp_data_fit/'  ; Default directory for input data files

;
;  Generate list of files to process based on input parameter
;

if (N_PARAMS() EQ 1) then inp_dir = DEF_INP_DIR
lscmd = string(format='("ls -l ", 2A, " > SFPB.tmp.in")', inp_dir, inp_fil)
spawn, lscmd
openr,7, 'SFPB.tmp.in'
file = ' '
inp = ' '

while (NOT EOF(7)) do begin

      readf,7,inp
      work = strsplit(inp,' ',/extract)
      file = work(8)
      chk_target, file, DEBUG=debug, OUTF=outf, DISSERT=dissert

endwhile

close,7
spawn,'rm -f SFPB.tmp.in'

return
end

;***************************************************************************
;   END OF SFPB                                                            *
;***************************************************************************
```

```
;*************************************************************************
; CHK_TARGET                                                             *
;                                                                        *
;   Check specified target for secondary packet and generate the         *
;   diagnostic plots.                                                    *
;                                                                        *
;*************************************************************************

pro chk_target, curfil, DEBUG=debug, OUTF=outf, DISSERT=dissert

;
;  Define constants
;
MINDATS = 1501        ; Minimum number data scans in input data
L_PASS = 20           ; Wavelength lower-limit for low-pass filter
BW = 30               ; Bandwidth (Hz) on each side of Nominal freq to use for bandpass filtering
MIN_SCW = 1.0         ; Minimum scan weight to identify good SNR scans
jj = 20               ; Index to use for plot of example scans
BASELINES = ['W2-S1', 'W2-S2', 'W2-E1', 'W2-E2', 'W2-W1', 'W1-S1', 'W1-S2', $
             'W1-E1', 'W1-E2', 'E2-S1', 'E2-S2', 'E2-E1', 'E1-S1', 'E1-S2', 'S2-S1']
; Default directory for output data files
if KEYWORD_SET(dissert) then DEF_OUT_DIR = '~/dissert/figures/sfp/' $
else DEF_OUT_DIR = '~/chara/red_data/'


!p.multi = 0
set_plot,'x'    ; default to terminal graphics output
!p.color=0
!p.background=19

;
;  Read FITS file and set header variables
;
fits_open, curfil, fitf
fits_read, fitf, fitdat, fithdr

BefShw = 1 * HDRVAL(fithdr, 'CCSHUTA ')  ; Width of "before" shutter sequence (in number-of-scan uni
ts)
AftShw = 1 * HDRVAL(fithdr, 'CCSHUTB ')  ; Width of "after" shutter sequence (in number-of-scan unit
s)
Wave_Lth = 1.e-6 * HDRVAL(fithdr, 'CCLAMBDA')  ; Wavelength (K band, m)

hd_id = long(STRMID(HDRVAL(fithdr, 'CCSTARHD'), 3))
fsplit = strsplit(curfil,'/', /EXTRACT)
nf = SIZE(fsplit, /DIMENSIONS)
scurfil = fsplit(nf(0)-1)  ; Short file name (w/o dir name)
seq_no = 1 * HDRVAL(fithdr, 'CCNUMBER')
seq_no = strmid(string(format='(I4)',1000+seq_no),1,3)  ; convert to 3 digit string

scope1 = strmid(HDRVAL(fithdr, 'CC_BEAM5'), 0, 2)
scope2 = strmid(HDRVAL(fithdr, 'CC_BEAM6'), 0, 2)
blname = scope1 + '-' + scope2
bl_num = where(blname EQ BASELINES)   ; Baseline number

utdate = HDRVAL(fithdr, 'CCUTDATE')
work   = strsplit(utdate, '-', /EXTRACT)  ; remove '-' separators
obs_yr = work(0)
obs_mo = work(1)
obs_dt = work(2)

uttime = HDRVAL(fithdr, 'CCUTTIME')
work   = strsplit(uttime, ' ', /EXTRACT)  ; remove ' ' separators
obs_hr = work(0)
obs_mn = work(1)
obs_sc = work(2)


;
;  Read dith, I_A, I_B into arrays
;
inpdat = dblarr(3)
dith = reform(fitdat(*,1,*))
I_A  = reform(fitdat(*,2,*))
I_B  = reform(fitdat(*,3,*))

ScanLth = 1 * HDRVAL(fithdr, 'CCNDATA ')      ; Nbr of samples per scan
NbrTotS = 1 * HDRVAL(fithdr, 'CCNSCANS')      ; Total nbr of scans
```

```
NbrDatS = 1 * HDRVAL(fithdr, 'CCDATSCN')      ; Nbr of data scans
SampleInt = 1.d / HDRVAL(fithdr, 'CCSAMPLE')  ; Sample rate in seconds
DithRange = 1.d * HDRVAL(fithdr, 'CCDRANGE')  ; Dither motion range (microns)

;
;  Skip if minimum number fo data scans not found
;

if (NbrDatS LT MINDATS) then begin
   print,format='("Input file: ", 1A)', curfil
   print,format='("Input file has only ", I6, " data scans")', NbrDatS
   print,format='("Minimum ", I6, " lines required, skipping this file")', MINDATS
   return
endif

;
;  PRINT HEADER INFO FOR TARGET
;

;
;  Format date/time for printing
;
put = string(format='(I4,"/",A2,"/",A2," ",A2,":",A2,":",F6.3)', $
      obs_yr, strmid(string(format='(I3)',obs_mo+100),1,2), $
      strmid(string(format='(I3)',obs_dt+100),1,2), $
      strmid(string(format='(I3)',obs_hr+100),1,2), $
      strmid(string(format='(I3)',obs_mn+100),1,2), $
      strmid(string(format='(F7.3)',obs_sc+100.),1,6))

if NOT KEYWORD_SET(dissert) then begin
   print,format='("Input file: ", 1A)', curfil
   print,format='("Reduced (ET): ", 1A)', systime()
   print,format='("HD: ", I6, "  Seq: ", A3, "  Baseline: ", A5, "  Obs Start (UT): ", A23)', $
       hd_id, seq_no, blname, put
endif

;  Set prefix of output file name
outfp = DEF_OUT_DIR + "HD" + strmid(string(format='(I7)',hd_id+1000000), 1, 6) + "_" + $
         strmid(blname,0,2) + strmid(blname,3,2) + "_" + $
         string(format='(I4)', obs_yr) + strmid(string(format='(I3)',obs_mo+100),1,2) + $
         strmid(string(format='(I3)',obs_dt+100),1,2) + "_" + seq_no + "."

if KEYWORD_SET(outf) then begin
   openw,2, outfp+"Header"
   printf, 2, format='("Input file: ", 1A)', curfil
   printf, 2, format='("Reduced (ET): ", 1A)', systime()
   printf, 2, format='("HD: ", I6, "  Seq: ", A3, "  Baseline: ", A5, "  Obs Start (UT): ", A23)', $
              hd_id, seq_no, blname, put
endif

;
;  Set positions for first shutter sequence
;

strbl = BefShw                  ; Index of left shutter seq start
strbd = strbl + BefShw          ; Index of dark start
strbr = strbd + BefShw          ; Index of right shutter seq start

;
;  Set positions for second shutter sequence
;

stral = 4 * BefShw + NbrDatS  ; Start index of left shutter seq
strad = stral + AftShw        ; Start index of dark
strar = strad + AftShw        ; Start index of right shutter seq


Indfss = 4 * BefShw           ; Index of first signal scan (after initial shutter sequence)
Indlss = Indfss + NbrDatS - 1 ; Index of last signal scan (before final shutter sequence)

if NOT KEYWORD_SET(dissert) then begin
   print,format='("    Indfss = ", I6, "    Scan Length = ", I4)', Indfss, ScanLth
   print,format='("    Total Nbr of Scans = ", I4, "   Nbr of Data Scans =", I4)', NbrTotS, NbrDatS
   print,format='("    WvLth (um) = ", F5.3, "   Dither range (um) = ", F8.4, "  Samples per sec = "
, F7.3)', $
              1.e6*Wave_Lth, DithRange, 1.d/SampleInt
endif

if KEYWORD_SET(outf) then begin
```

```
   printf,2,format='("    Indfss = ", I6, "    Scan Length = ", I4)', Indfss, ScanLth
   printf,2,format='("    Total Nbr of Scans = ", I4, "   Nbr of Data Scans =", I4)', NbrTotS, NbrDa
tS
   printf,2,format='("    WvLth (um) = ", F5.3, "   Dither range (um) = ", F8.4, "  Samples per sec
= ", F7.3)', $
                     1.e6*Wave_Lth, DithRange, 1.d/SampleInt
endif

;
;  PLOT SHUTTER POSITIONS TO VERIFY AND CONTINUE
;

plot_x = indgen(1l*NbrTotS*ScanLth, /long)
plot_x = REFORM(plot_x, [ScanLth, NbrTotS])

if NOT KEYWORD_SET(dissert) then begin

   window,1, retain=2, xsize=1000,ysize=300, xpos=0, ypos=500, $
        title=curfil + " " + blname
   plot,plot_x, I_A, Title='Beam A data'
;  Overplot shutter points in gray
   oplot,plot_x(*, BefShw:4l*BefShw-1), I_A(*, BefShw:4l*BefShw-1), color = 12
   oplot,plot_x(*, stral:NbrTotS-BefShw-1),I_A(*, stral:NbrTotS-BefShw-1), $
         color = 12
;  Overplot signal points in blue
   oplot,plot_x(*, Indfss:stral-1), I_A(*, Indfss:stral-1), color = 96

   window,2, retain=2, xsize=1000,ysize=300, xpos=0, ypos=150, $
        title=curfil + " " + blname
   plot,plot_x, I_B, Title='Beam B data'
;  Overplot shutter points in gray
   oplot,plot_x(*, BefShw:4l*BefShw-1),I_B(*, BefShw:4*BefShw-1), color = 12
   oplot,plot_x(*, stral:NbrTotS-BefShw-1),I_B(*, stral:NbrTotS-BefShw-1), $
        color = 12
;  Overplot signal points in blue
   oplot,plot_x(*, Indfss:stral-1), I_B(*, Indfss:stral-1), color = 96

endif


;
;  Plot to output file
;
if KEYWORD_SET(outf) then begin
   set_plot,'ps'
   device,filename=outfp+'InpData.eps',/landscape
   plot, plot_x, I_A, Title='Beam A data', subtitle = curfil + " " + blname
   oplot,plot_x(*, BefShw:4*BefShw-1), I_A(*, BefShw:4*BefShw-1), color = 12
   oplot,plot_x(*, stral:NbrTotS-BefShw-1), I_A(*, stral:NbrTotS-BefShw-1), $
         color = 12
   oplot,plot_x(*, Indfss:stral-1), I_A(*, Indfss:stral-1), color = 96
   plot, plot_x, I_B, Title='Beam B data', subtitle = curfil + " " + blname
   oplot,plot_x(*, BefShw:4*BefShw-1), I_B(*, BefShw:4*BefShw-1), color = 12
   oplot,plot_x(*, stral:NbrTotS-BefShw-1), I_B(*, stral:NbrTotS-BefShw-1), $
        color = 12
   oplot,plot_x(*, Indfss:stral-1), I_B(*, Indfss:stral-1), color = 96
   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
   !p.color=0
   !p.background=19
endif

;
;  Calculate dither mirror velocity in m/s
;    Dither step is in microns
;    Time elapsed b/w consecutive dither mirror steps = SampleInt (s)
;    Multiply by 2 due to accont for reflection off mirror
;    (Delta light path = 2 * mirror movement)
;

frdi = fix(ScanLth*0.2) ; As dither velocity is not uniform at edges,
todi = fix(ScanLth*0.8) ; take midle 60%
DithVel = ABS(dith(todi, jj) - dith(frdi, jj)) / (todi-frdi) * 2.d / (SampleInt * 1.e6)  ; jj-th sca
n taken as repr

;
;  Nominal Fringe Frequency
;
```

```
Freq0   = round(DithVel/Wave_Lth)        ; Fringe Freq Calc
FrgFreq = 1 * HDRVAL(fithdr, 'CCDFREQ ')  ; Fringe Freq from FITS

if NOT KEYWORD_SET(dissert) then begin
   print, format = '("Dither mirror velocity = ", F8.6, " mm/s")', $
          DithVel * 1000.d
   print, format = '("Nominal Fringe Frequency: Calc = ", F5.1, ", From FITS = ", F5.1, " Hz")', Fre
q0, FrgFreq
endif

if KEYWORD_SET(outf) then begin
   printf,2,format = '("Dither mirror velocity = ", F8.6, " mm/s")', DithVel * 1000.d
   printf,2,format = '("Nominal Fringe Frequency: Calc = ", F5.1, ", From FITS = ", F5.1, " Hz")', F
req0, FrgFreq
endif


if KEYWORD_SET(debug) then stop,'Review shutter and signal positions, then enter .c to continue' $
else if NOT KEYWORD_SET(dissert) then wait,2

;
;  Calculate and subtract dark (bias) from IA & IB
;

;  Beam A - Calculate dark (bias)
;
darkIAb = MEAN(I_A(*, strbd:strbd+BefShw-1))
sig_darkIAb = STDDEV(I_A(*, strbd:strbd+BefShw-1))
darkIAa = MEAN(I_A(*, strad:strad+AftShw-1))
sig_darkIAa = STDDEV(I_A(*, strad:strad+AftShw-1))
darkA = 0.5*(darkIAb+darkIAa)
sig_darkA = 0.5*(sig_darkIAb+sig_darkIAa)
;
;  Beam B - Calculate dark (bias)
;
darkIBb = MEAN(I_B(*, strbd:strbd+BefShw-1))
sig_darkIBb = STDDEV(I_B(*, strbd:strbd+BefShw-1))
darkIBa = MEAN(I_B(*, strad:strad+AftShw-1))
sig_darkIBa = STDDEV(I_B(*, strad:strad+AftShw-1))
darkb = 0.5*(darkIBb+darkIBa)
sig_darkB = 0.5*(sig_darkIBb+sig_darkIBa)

if NOT KEYWORD_SET(dissert) then begin
   print,format='("    darkA = ", F5.1, "     darkB = ", F5.1)', darkA, darkB
   print,format='("sig_darkA = ", F5.1, " sig_darkB = ", F5.1)', sig_darkA, sig_darkB
endif
if KEYWORD_SET(outf) then begin
   printf,2,format='("    darkA = ", F5.1, "     darkB = ", F5.1)', darkA, darkB
   printf,2,format='("sig_darkA = ", F5.1, " sig_darkB = ", F5.1)', sig_darkA, sig_darkB
endif

I_A = I_A - darkA
I_B = I_B - darkB


;
;   Calculate shutter input factors
;

;  Beam A - Calculate shutter input factors
;
avIAbl = MEAN(I_A(*, strbl:strbl+BefShw-1))
avIAbr = MEAN(I_A(*, strbr:strbr+BefShw-1))
avIAal = MEAN(I_A(*, stral:stral+AftShw-1))
avIAar = MEAN(I_A(*, strar:strar+AftShw-1))
IAS1 = 0.5d*(avIAbl + avIAal)
IAS2 = 0.5d*(avIAbr + avIAar)

;  Beam B - Calculate shutter input factors
;
avIBbl = MEAN(I_B(*, strbl:strbl+BefShw-1))
avIBbr = MEAN(I_B(*, strbr:strbr+BefShw-1))
avIBal = MEAN(I_B(*, stral:stral+AftShw-1))
avIBar = MEAN(I_B(*, strar:strar+AftShw-1))
IBS1 = 0.5d*(avIBbl + avIBal)
IBS2 = 0.5d*(avIBbr + avIBar)

if NOT KEYWORD_SET(dissert) then begin
   print,format='("    IAS1 = ", F5.1, "     IAS2 = ", F5.1)', IAS1, IAS2
```

```
   print,format='("    IBS1 = ", F5.1, "     IBS2 = ", F5.1)', IBS1, IBS2
endif
if KEYWORD_SET(outf) then begin
   printf,2,format='("    IAS1 = ", F5.1, "     IAS2 = ", F5.1)', IAS1, IAS2
   printf,2,format='("    IBS1 = ", F5.1, "     IBS2 = ", F5.1)', IBS1, IBS2
endif

;
;  LOAD DATA SCANS (EXCLUDING SHUTTER SEQ) INTO A 2-D ARRAY
;    j = Scan number 0..NbrDatS-1  (first index)
;    k = Dither steps for each scan 0..ScanLth-1  (second index)
;

SIA =    TRANSPOSE(I_A(*, Indfss:Indlss))
SIB =    TRANSPOSE(I_B(*, Indfss:Indlss))
dither = TRANSPOSE(dith(*, Indfss:Indlss))

;
;  Print dither arrays to verify that slicing of scans is
;  appropriately done.  Should see a clean X in the plot if
;  everything is OK and there is no drift in slicing the scans.
;  A drifting i.e wide X in the plot indicates a problem.
;
if NOT KEYWORD_SET(dissert) then begin
   wset,2
   plot,dither(0,*), title = 'Dither positions to verify scan slicing'
   for j = 1, NbrDatS - 1 do oplot, dither(j,*)
endif

if KEYWORD_SET(debug) then stop,'Review dither positions i.e scan slicing, then enter .c to continue
' $
else if NOT KEYWORD_SET(dissert) then wait,2

;
;  Normalize A & B scans before combining
;

nSIA = SIA / AVG(SIA)
nSIB = SIB / AVG(SIB)

;
;  Combine light from A & B sides for further processing
;  Take average of A & B side, accounting for sign difference
;  as they are 180d out of phase.
;

SigScan = (nSIA - nSIB) / 2.0d  ; Average A & B

;
;  FLIP ALTERNATE SCANS TO ALIGN ALL SCANS IN THE SAME DIRECTION
;
;  Dither mirror moves back and forth while scanning so that each
;  scan is in the opposite ditection of the previous/next scan.
;

jind = indgen(NbrDatS)
jodd = jind(where(jind MOD 2 NE 0))  ; Odd indices

tSigScan = SigScan
for k = 0, ScanLth - 1 do begin
    tSigScan(jodd,k) = SigScan(jodd,ScanLth-1-k)
endfor
SigScan = tSigScan

;
;  PERFORM FT ON SIGNAL TO WORK IN FREQUENCY DOMAIN
;

FSig = dcomplexarr(NbrDatS, ScanLth)

for j = 0, NbrDatS - 1 do begin

    FSig(j,*) = FFT(SigScan(j,*), -1)  ; Fast Fourier transform

endfor

;
;  SETUP THE FREQUENCY ARRAY FOR FFT RESULTS (see IDL help
;  for even and odd numbered arrays).
```

```
;  For even number of elements, freq = [0,1/NT, 2/NT, .. ,(N/2-1)/NT,
;  then mirror image for negative freq]
;  For odd number of elements, freq = [0,1/NT, 2/NT, .. ,(N-1)/2NT,
;  then mirror image for negative freq]
;  e.g. if N=10, T=2s, freq are:
;  [0, 1/20, 2/20, 3/20, 4/20, 5/20, -4/20, -3/20, -2/20, -1/20]
;  if N=9, T=2s, freq are:
;  [0, 1/18, 2/18, 3/18, 4/18, -4/18, -3/18, -2/18, -1/18]
;

nposf = long(ScanLth/2.) + 1l  ; number of positive freq (incl 0)
FTfreq = findgen(nposf)/(ScanLth*SampleInt)
nposi = long((ScanLth+1)/2.) - (indgen(long((ScanLth-1)/2.)) + 1) ; index of repeated frequencies
FTfreq = [FTfreq, -1.d * FTfreq(nposi)]

;
;  IDENTIFY NOISE SCANS (scans without a fringe) AND ELIMINATE THEM
;
;  A scan is considered to contain a fringe when the power in the vicinity
;  of the fringe frequency is greater than the power in the adjoining
;  higher frequency range.  e.g.  for fringe freq = 150 Hz and
;  bandwidth = 30 Hz, power in range (120 - 180 Hz) is compared
;  with power in range (181 - 241 Hz) to assign a scan weight.
;

;  Fringe frequency range & indices:
strfrg = FrgFreq - BW
stpfrg = FrgFreq + BW
xfrg_freqi = where(ABS(FTFreq) LT strfrg OR ABS(FTFreq) GT stpfrg) ; indices outside fringe width
;  Off fringe (high frequency) range & indices:
stroff = FrgFreq + BW + 1
stpoff = stroff + 2*BW
xoff_freqi = where(ABS(FTFreq) LT stroff OR ABS(FTFreq) GT stpoff) ; indices outside high-freq width

scan_wt = fltarr(NbrDatS)  ; Scan Weight (measure of SNR)

uPS = FSig * CONJ(FSig)  ; Unfiltered Power Spectrum

for j = 0, NbrDatS - 1 do begin

    tPS = uPS(j,*)
    tPS(xfrg_freqi) = 0.0d
    tot_frg_pow = TOTAL(tPS)

    tPS = uPS(j,*)
    tPS(xoff_freqi) = 0.0d
    tot_off_pow = TOTAL(tPS)

    scan_wt(j) = (tot_frg_pow - tot_off_pow) / tot_off_pow

endfor

;
;  Select good SNR scans
;
gsi = where(scan_wt GE MIN_SCW)  ; good SNR scan indices
Ngscans = SIZE(gsi, /DIMENSIONS) ; Number of good scans
gSigScan = SigScan(gsi, *)       ; Subset of good scans
FgSig = FSig(gsi, *)             ; Subset of FTs of good scans
guPS = uPS(gsi, *)               ; Subset of unfiltered PS

if NOT KEYWORD_SET(dissert) then begin
   print, format='("Good SNR scans = ", I3, " / ", I4)', Ngscans(0), NbrDatS
endif
if KEYWORD_SET(outf) then begin
   printf,2,format='("Good SNR scans = ", I3, " / ", I4)', Ngscans(0), NbrDatS
endif

if (Ngscans(0) LT jj + 10) then begin  ; Not enough good scans, skip
   if KEYWORD_SET(outf) then $
      printf,2,'Not enough good scans found, skipping target!'
   if NOT KEYWORD_SET(dissert) then $
      stop,'Not enough good scans found, skipping target; enter .c to continue'
   if KEYWORD_SET(outf) then close,2
   return
endif


FSig = FgSig
```

```
SigScan = gSigScan
NScans = Ngscans(0)
uPS = guPS

;
;  Plot histogram of scan weights as a indicator of seeing
;

gsw = scan_wt(gsi)  ; Good (selected) scan weights
swi = sort(gsw)     ; Sort indices in ascending order
avg_wt = AVG(gsw)
sdev_wt = STDDEV(gsw)
if NOT KEYWORD_SET(dissert) then begin
   print, format='("Scan weights: Avg = ", F4.1, "  SDev = ", F4.1)', $
       avg_wt, sdev_wt
endif
if KEYWORD_SET(outf) then $
   printf,2,format='("Scan weights: Avg = ", F5.1, "    SDev = ", F5.1)', $
            avg_wt, sdev_wt

binincr = 1   ; increment of histogram bins
BINARRAY, gsw, binincr, bin, binct

if NOT KEYWORD_SET(dissert) then begin
   wset,2
   maxy = max(binct)+1
   plot, bin, binct, title = 'Histogram of Scan Weights', psym=10, $
      xrange=[0,max(scan_wt)+1], yrange=[0,maxy], $
      xtitle='Scan Weight', ytitle='Number of Scans'
   oplot,[avg_wt,avg_wt],[0,maxy], linestyle=2
   oplot,[avg_wt-sdev_wt, avg_wt+sdev_wt], [1,1], linestyle=2
endif

if KEYWORD_SET(debug) then stop,'Review scan weights, then enter .c to continue' $
else if NOT KEYWORD_SET(dissert) then wait,2



;
;  PERFORM LOW-PASS FILTER TO REMOVE LOW FREQ NOISE
;

lp_freqi = where(ABS(FTfreq) LE L_PASS) ; indices in LP filter
lpfi = dblarr(ScanLth)
lpfi(lp_freqi) = 1  ; Select freq below L_PASS

lpfilt = dcomplexarr(NScans, ScanLth)
LPSig = dcomplexarr(NScans, ScanLth)
lpPS = dcomplexarr(NScans, ScanLth)

for j = 0, NScans - 1 do begin

    lpfilt(j,*) = FFT(FSig(j,*)*lpfi, 1)     ; LP filter (low freq modulation)
    LPSig(j,*) = FFT(FSig(j,*)*(1-lpfi), 1)  ; LP filtered signal (low freq mod taken out)
    lpPS(j,*) = uPS(j,*) * (1-lpfi)          ; LP filtered PS

endfor

if NOT KEYWORD_SET(dissert) then begin
   window,3, retain=2, xsize=350,ysize=550, xpos=300, ypos=250, $
        title=scurfil + " " + blname
   miny = MIN(SigScan(jj,*)) - 0.05 * MIN(SigScan(jj,*))
   maxy = 10 * (MAX(SigScan(jj,*)) - miny)
   plot,[0],[0], title='Example signal scans', xrange=[0,ScanLth-1], $
              yrange=[miny,maxy]
   for jp = 0, 9 do oplot, SigScan(jj+jp,*) + jp*maxy/10
   for jp = 0, 9 do oplot, lpfilt(jj+jp,*) + jp*maxy/10, color=96, thick=2

   window,4, retain=2, xsize=350,ysize=550, xpos=660, ypos=250, $
        title=scurfil + " " + blname
   miny = MIN(FLOAT(LPSig(jj,*))) - 0.05 * MIN(FLOAT(LPSig(jj,*)))
   maxy = 10 * (MAX(FLOAT(LPSig(jj,*))) - miny)
   plot,[0],[0], title='Example LP filtered scans', xrange=[0,ScanLth-1], $
              yrange=[miny,maxy]
   for jp = 0, 9 do oplot,LPSig(jj+jp,*)+jp*maxy/10.
endif

if KEYWORD_SET(debug) then stop,'Review low-pass filtering and enter .c to continue' $
else if NOT KEYWORD_SET(dissert) then wait,2
```

```
;
;  PLOT LOWPASS FILTERED POWER SPECTRUM EXAMPLES AND AVERAGE PS
;

if NOT KEYWORD_SET(dissert) then begin
   wset,3
   minx = FTfreq(0)
   maxx = FTfreq(ScanLth/2-1)
   plot,[0],[0], title='LP filtered PS', xrange=[minx,maxx], $
              yrange=[-1,11]
   for jp = 0, 9 do oplot, $
       FTfreq(0:ScanLth/2-1), lpPS(jj+jp,0:ScanLth/2-1)/MAX(lpPS(jj+jp,*)) + jp
endif

;
;  Plot average low-pass filtered power spectrum
;

alpPS = dcomplexarr(ScanLth)
for k = 0, ScanLth - 1 do alpPS(k) = AVG(lpPS(*,k))
maxy = MAX(alpPS) * 1.05

if NOT KEYWORD_SET(dissert) then begin
   window,2, retain=2, xsize=500,ysize=300, xpos=510, ypos=80, $
        title=curfil + " " + blname
   plot,FTfreq(0:ScanLth/2-1),alpPS, title='Average Power Spectrum', $
           yrange=[0,maxy]
endif

;
;  Overplot BP filter frequency range
;

low = FrgFreq - BW
high = FrgFreq + BW
xbp_freqi = where(ABS(FTFreq) LT low OR ABS(FTFreq) GT high) ; indices outside BP filter
bpfilt = intarr(ScanLth/2-1)
bpfilt = bpfilt+maxy
bpfilt(xbp_freqi) = 0
if NOT KEYWORD_SET(dissert) then begin
   oplot,FTfreq(0:ScanLth/2-1),bpfilt,linestyle=2
endif

if KEYWORD_SET(outf) then begin
   set_plot,'ps'
   device,filename=outfp+'PS.eps',/landscape
   plot,FTfreq(0:ScanLth/2-1), alpPS, Title='Average Power Spectrum', subtitle = curfil + " " + blna
me
   oplot,FTfreq(0:ScanLth/2-1),bpfilt,linestyle=2
   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
   !p.color=0
   !p.background=19
endif

if KEYWORD_SET(debug) then stop, 'Review Power Spectrum and enter .c to continue' $
else if NOT KEYWORD_SET(dissert) then wait,2

;
;  PERFORM BANDPASS FILTERING
;
;  Weight frequencies within "BW" of nominal fringe frequency as 1 and
;  supress frequencies outside this range by weighting as 0.1,
;  then inverse FT to get banpass filtered signal
;

FSig = dcomplexarr(NScans, ScanLth)

for j = 0, NScans - 1 do begin

    FSig(j,*) = FFT(LPSig(j,*), -1)  ; FT the signal to convert to frequency domain

endfor

FSig(*, xbp_freqi) = 0.1d * FSig(*, xbp_freqi)

BPSig = dcomplexarr(NScans, ScanLth)
```

```
for j = 0, NScans - 1 do begin

    BPSig(j,*) = FFT(FSig(j,*), 1)  ; Inverse FT to get BP filtered signal

endfor

;
;  GENERATE FRINGE ENVELOPE
;
;  This is done by  zeroing out negative frequencies on
;  the bandpass filtered FT and taking the modulus of the
;  inverse FT transform
;

negf = where(FTFreq LT 0.)
FSig(*, negf) = 0.0d             ; Zero out negative frequencies

FESig = dcomplexarr(NScans, ScanLth)

for j = 0, NScans - 1 do begin

    FESig(j,*) = FFT(FSig(j,*), 1)             ; Inverse FT to get signal

endfor

FE = 2 * ABS(FESig) ; Twice the mod (twice b/c neg freq suppressed)

miny = MIN(SigScan(jj,*)) - 0.05 * MIN(SigScan(jj,*))
maxy = 10 * (MAX(SigScan(jj,*)) - miny)

if NOT KEYWORD_SET(dissert) then begin
   window,3, retain=2, xsize=350,ysize=550, xpos=300, ypos=250, $
        title=scurfil + " " + blname
   plot,[0],[0], title='Example Scans Before BP filtering', $
              xrange=[0,ScanLth-1],yrange=[miny,maxy]
   for jp = 0, 9 do oplot,LPSig(jj+jp,*)+jp*maxy/10.

   window,4, retain=2, xsize=350,ysize=550, xpos=660, ypos=250, $
        title=scurfil + " " + blname
   plot,[0],[0], title='Example BP filtered Fringes with Envelope', $
              xrange=[0,ScanLth-1],yrange=[miny,maxy]
   for jp = 0, 9 do oplot, BPSig(jj+jp,*) + jp*maxy/10.  ; Plot fringes
   for jp = 0, 9 do oplot, FE(jj+jp,*) + jp*maxy/10., color=240 ; Overplot FE
endif

if KEYWORD_SET(debug) then stop,'Review bandpass filtering & fringe envelopes, then enter .c to cont
inue' $
else if NOT KEYWORD_SET(dissert) then wait,2

;
;  SHIFT INDIVIDUAL FRINGE PEAKS TO ALIGN AND SUM SHIFTED FRINGES
;
;  This is a tool used to detect a secondary fringe
;  Steps:
;  1. Select the scan with maximum fringe weight as standard.
;  2. Shift the peak of this scan to the center
;  3. Cross-correlate each fringe wrt to the standard
;  4. Find maximum of cross correlation function
;  5. Shift scan by this amount plus shift of the standard scan
;  6. Add all shifted scans
;  7. Center the peak of the summed FE and plot
;

gsw = scan_wt(gsi)  ; Scan weight subset of good scans
sgsw = reverse(sort(gsw))  ; sort indices in descending order
bestj = sgsw(0)  ; index of best scan
BestFE = FE(bestj,*)
max = MAX(BestFE, maxi)
ctri = long(Scanlth/2)
sftb = ctri - maxi   ; indices to shift best FE to center
clag = indgen((NScans-2)*2+1) - (NScans-2)  ; max allowed range for c-corr lag
plot_x = INDGEN(ScanLth) - ctri

SCFE = DCOMPLEXARR(ScanLth)  ; Shifted FE
for j = 0, NScans - 1 do begin

    CurFE = FE(j,*)
    ccorr = C_CORRELATE(BestFE, CurFE, clag)
    mxc = max(ccorr, sftc)
```

```
    sfti = sftb - clag(sftc) ; indices to shift by
;   Note: IDL SHIFT routine wraps array around, and we do not want
;   that!  So, manullay zero out padded values.
    sCurFE = SHIFT(CurFE, sfti)
    if (sfti GT 0) then sCurFE(0:sfti-1) = 0. $
    else sCurFE(ScanLth-1+sfti:ScanLth-1) = 0.

    SCFE(*) = SCFE(*) + sCurFE

endfor

SCFE = SCFE / MAX(SCFE)  ; Normalize
;
;  Shift peak to center
;
max = MAX(SCFE, maxi)
sfti = ctri - maxi ; indices to shift by
SCFE = SHIFT(SCFE, sfti)
if (sfti GT 0) then sCFE(0:sfti-1) = 0. $
else SCFE(ScanLth-1+sfti:ScanLth-1) = 0.

if NOT KEYWORD_SET(dissert) then begin
   window, 5, retain=2, xsize=350,ysize=350, xpos=0, ypos=450, $
        title=scurfil + " " + blname
   plot,plot_x,SCFE, title='Cross-corr shifted fringe envelopes', $
        yrange=[0,1]
endif

;
;  AUTO-CORRELATE FRINGE ENVELOPES TO HELP DETECT A SECONDARY FRINGE
;
;  Auto-correlation = Inverse-FT (FT * CONJ(FT))
;  ACor = Sum of auto-correlation of each fringe scan
;

ACor = DCOMPLEXARR(ScanLth)

for j = 0, NScans - 1 do begin

    FFE = FFT(FE(j,*), -1)                         ; FT of Fringe Envelope
    ACor(*) = ACor(*) + FFT((FFE*CONJ(FFE)), 1)  ; Autocorrelation

endfor

ACor = SHIFT(ACor, ctri)  ; Shift to place primary-peak in the center

Acor = Acor / MAX(Acor)  ; Normalize
if NOT KEYWORD_SET(dissert) then begin
   window,3, retain=2, xsize=350,ysize=350, xpos=300, ypos=450, $
        title=scurfil + " " + blname
   plot,plot_x,Acor, title='Autocorrelation of fringe envelopes', $
     yrange=[0,1]
endif

;
;  SHIFT INDIVIDUAL FRINGE PEAKS TO CENTER AND SUM SHIFTED FRINGES
;
;  This is another tool used to detect a secondary fringe
;

SFE = DCOMPLEXARR(ScanLth)  ; Shifted FE
for j = 0, NScans - 1 do begin

    CurFE = FE(j,*)
    max = MAX(CurFE, maxi)
    sfti = ctri - maxi ; indices to shift by
    sCurFE = SHIFT(CurFE, sfti)
    if (sfti GT 0) then sCurFE(0:sfti-1) = 0. $
    else sCurFE(ScanLth-1+sfti:ScanLth-1) = 0.
    SFE(*) = SFE(*) + sCurFE

endfor

SFE = SFE / MAX(SFE)  ; Normalize
if NOT KEYWORD_SET(dissert) then begin
   window,4, retain=2, xsize=350,ysize=350, xpos=660, ypos=450, $
        title=scurfil + " " + blname
   plot,plot_x,SFE, title='Sum of shifted fringe envelopes', $
     yrange=[0,1]
```

```
endif

;
;; Plot the PS version of above 3 plots
;

if KEYWORD_SET(dissert) then begin
   !p.multi = [0, 3, 2, 0, 0]    ; xp x yp panes
   set_plot,'ps'
   device,filename=outfp+'FEsummary.eps',/landscape
   plot,plot_x,SCFE, $ ; title='Cross-corr shifted fringe envelopes', $
;        subtitle = curfil + " " + BASELINES(bl_num), yrange=[0,1]
       charsize=1.8, xthick=4, ythick=4, charthick=4, thick=4, $
       yrange=[0.,1.05], xtickinterval=100, $
       xtitle='Relative offset', ytitle='Intensity'
   plot,plot_x,Acor, $ ; title='Autocorrelation of fringe envelopes', $
;        subtitle = curfil + " " + BASELINES(bl_num), yrange=[0,1]
       charsize=1.8, xthick=4, ythick=4, charthick=4, thick=4, $
       yrange=[0,1.05], xtickinterval=100, $
       xtitle='Relative offset', ytitle='Intensity'
   plot,plot_x,SFE, $ ;title='Sum of shifted fringe envelopes', $
;        subtitle = curfil + " " + BASELINES(bl_num), yrange=[0,1]
       charsize=1.8, xthick=4, ythick=4, charthick=4, thick=4, $
       yrange=[0,1.05], xtickinterval=100, $
       xtitle='Relative offset', ytitle='Intensity'
;
;  Plot 12 strongest FE below this
;
   !p.multi = [14, 7, 4, 0, 0]    ; xp x yp panes
   maxy = MAX(FE, MIN=miny)
   for pp = 0, 13 do begin
       if (pp LT Nscans) then $
          plot, plot_x, FE(sgsw(pp),*), $
;               title = string(format='("FE ",I3)', sgsw(cp)), $
                yrange=[miny,maxy], $
                xcharsize=0.1, xthick=4, ythick=4, charthick=4, thick=4, $
;                xtitle='Relative offset', ytitle='Intensity', $
                xtickinterval=200, ycharsize=0.1, ytickv=['','','','',''], $
                xtickv=['','']
   endfor

   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
   !p.color=0
   !p.background=19
   !p.multi = 0

endif


if KEYWORD_SET(debug) then stop, 'Enter .c to see individual fringe envelopes' $
else if NOT KEYWORD_SET(dissert) then WAIT,4

;
;  PLOT INDIVIDUAL FRINGE ENVELOPES
;
;  Plot them in order of scan_wt, descending so that "best"
;  scans are displayed first.
;  Keep Y-axis scale same across all plots to facilitate
;  comparison of the relative strengths of fringe envelopes
;

maxy = MAX(FE, MIN=miny)

if NOT KEYWORD_SET(dissert) then begin

   window, 6, retain=2, xsize=1000,ysize=700, xpos=0, ypos=100, $
        title=curfil + " " + blname
   xp = 7   ; number of panes in X direction
   yp = 6   ; number of panes in Y direction
   !p.multi = [0, xp, yp, 0, 0]    ; xp x yp panes
   ppp = xp * yp   ; plots per page
   npg = fix(NScans / ppp)  ; Number of pages
   if (NScans MOD ppp NE 0) then npg = npg + 1

   for pg = 0, npg - 1 do begin

       for pp = 0, ppp - 1 do begin
```

```
        cp = pg * ppp + pp   ; Current plot
        if (cp LT NScans) then $
            plot, plot_x, FE(sgsw(cp),*), title = string(format='("FE ",I3)', sgsw(cp)), $
                  yrange=[miny,maxy]

       endfor

       if KEYWORD_SET(debug) then  stop, 'Enter .c to go to next page' $
       else WAIT,4
   endfor
   wdelete,6
endif

;
;  Print individual FE to .eps file
;
if KEYWORD_SET(outf) then begin
   !p.multi = [0, xp, yp, 0, 0]    ; xp x yp panes
   set_plot,'ps'
   device,filename=outfp+'FEplots.eps',/landscape
   for pg = 0, npg - 1 do begin
       for pp = 0, ppp - 1 do begin
           cp = pg * ppp + pp   ; Current plot
           if (cp LT NScans) then $
              plot, plot_x, FE(sgsw(cp),*), title = string(format='("FE ",I3)', sgsw(cp)), $
                    yrange=[miny,maxy]
       endfor
   endfor
   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
   !p.color=0
   !p.background=19
endif

!p.multi = 0
if KEYWORD_SET(outf) then close,2

if NOT KEYWORD_SET(dissert) then begin
   stop, "Review " + scurfil + " and enter .c to continue"
endif
return
end

;****************************************************************************
;   END OF CHK_TARGET                                                       *
;****************************************************************************


;****************************************************************************
;  This procedure accepts an array,and a bin interval and returns two      *
;  other arrays:                                                            *
;  one with the values of bin intervals, and another with the              *
;  number of elements in original array with values between current        *
;  and next bin interval.  This is useful for plotting histograms.         *
;  Input parameter: inparr, binincr.  Output parameters: bin, binct        *
;****************************************************************************

pro BINARRAY,inparr,binincr,bin,binct

s = size(inparr)        ; determine size
maxind = s(1) - 1       ; second elemenet of s contains size of 1st dim

iamax = max(inparr, min=iamin)
bin = fix(iamin)                        ; truncate to integer
if (bin LT 0) then bin = bin - 1        ; e.g if bin = -18.2, set to -19

binct = 0
iasort = sort(inparr)

i = 0           ; bin counter
si = 0          ; srt index counter
done = 0
while (done EQ 0) do begin

        binmax = bin(i) + binincr

        while (done EQ 0 and inparr(iasort(si)) LT binmax) do begin

                binct(i) = binct(i) + 1
```

```
                if (si LT maxind) then si = si + 1 $
                else done = 1

        endwhile

        if (done EQ 0) then begin
                bin = [bin, bin(i) + binincr]   ; create next bin
                binct = [binct,0]        ; create next bin count
                i = i + 1                ; incr bin counter
        endif

endwhile

return
end

;*************************************************************************
;   END OF BINARRAY                                                      *
;*************************************************************************



;*************************************************************************
;   FUNCTION HDRVAL
;   For a given header array and a header parameter value interested,
;   return the corresponding parameter value
;   Usage hval = HDRVAL(header, hfld)
;*************************************************************************

function hdrval, hdr, hfld

hval = 'FLD NOT FOUND!'   ; Default error value

for i = 0, N_elements(hdr)-1 do begin

    work = strsplit(hdr(i), "=", /EXTRACT)

    if (work(0) EQ hfld) then begin
       work1 = strsplit(strmid(work(1),1,strlen(work(1))-1), "/", /EXTRACT)
       hval = work1(0)
       work1 = strsplit(work1(0), "'", /EXTRACT)  ; Remove single quotes, if present
       hval = work1(0)
       BREAK

   endif

endfor

return, hval

end
```

C.4 Blinking Archival Images

```
;  Program to blink DSS (or other) fits images to find CPM companions.
;  Original version obtained from W.C.Jao April 2006
;  Modified by Deepak Raghavan
;  Program prerequisites:
;  Obtain fits files in 2 epochs for taregt list
;  Note: To download DSS images from the web, use dss.sub.pl PERL
;        script written by WCJ
;
;  Parameters:
;    fitsdir = Directory containing FITS images
;  Keyword parameters:
;   OUTF = If set, results are appended to OUTFILE

pro fitsblink, fitsdir, OUTF=outf

BL_SIZE = 15  ; Size of image to blink
              ;  If image is larger, program will blink
              ;  image of size BL_SIZE from each corner of larger image
              ;  e.g. if downloaded image is 22' x 22', the code will
              ;  blink 15' x 15' from each corner of the 22' image.
DSS1_RESOL = 1.7  ; arcsec per pixel of DSS1 (lower resol) image
OUTFILE = '~/dss/DSSblinkResults'
DEF_FITSDIR = '/nfs/morgan2/raghavan/dss_images/'

if (N_PARAMS() EQ 0) then  fitsdir = DEF_FITSDIR


lsfits = ('ls ' + fitsdir + '*.fits' + '> ./fitsblink.in')
spawn, lsfits

loadct, 0  ; load B&W color table
!p.color = 255 ; Print white on black
!p.charsize = 1.0

; Load fits file list into array
openr, 1, './fitsblink.in'
data=''
readf, 1, data
fitslist = data
while not eof(1) do begin
      READF, 1, data
      fitslist = [fitslist, data]
endwhile
close,1

;  Set pointer in fits list for starting HIP number
print,'Enter number of stars to process:'
read,nproc
strind = -1
strhip = ' '
while (strind LT 0) do begin
    print,'Enter starting HIP number (Format=HIPnnnnnn):'
    read,strhip
    strind = where(fitslist EQ fitsdir + strhip + '.dss1.fits')
endwhile

openw,2,'./temp.out'
print,'Date/Time Processed   Target    Rotation Primary X/Y pos    Comp X/Y pos   Sep "  Pos-Ang'
if (KEYWORD_SET(outf)) then $
   printf,2,'Date/Time Processed   Target    Rotation Primary X/Y pos    Comp X/Y pos   Sep "  Pos-A
ng'

curnbr = 0
for j = strind(0), strind(0)+nproc*2-1, 2 do begin

    curnbr = curnbr + 1
    parse = strsplit(fitslist(j), "/", /EXTRACT)
    starid = strmid(parse(n_elements(parse)-1),0,9)
    dt = strmid(systime(),20,4)+' '+strmid(systime(),4,16) ; Get curr date/time
    fits_open,fitslist[j], fcb1
    fits_read, fcb1,dss1, header1
    word1  = sxpar(header1, 'DATE-OBS') ; obtain header parameter
    pltscl = sxpar(header1, 'PLTSCALE') ; plate scale in arcsec/mm
    xpixsz = sxpar(header1, 'XPIXELSZ') / 1000. ; X pixel size in mm
    ypixsz = sxpar(header1, 'YPIXELSZ') / 1000. ; Y pixel size in mm
    fits_close, fcb1
    epoch1=strsplit(word1,'T',/EXTRACT) ; split date & time

    fits_open,fitslist[j+1], fcb2
```

```
    fits_read, fcb2, dss2, header2
    word2=sxpar(header2, 'DATE-OBS')
    fits_close, fcb2
    epoch2=strsplit(word2, 'T',/EXTRACT)

;   DSS-1 resolution is 1.7"/pix, while DSS-2 res is 1"/pix
;   The following lines resize DSS-2 image to the size of DSS-1
;   while preserving total flux count
    dss1size=size(dss1,/dimension)

    xdss1size=dss1size[0]
    ydss1size=dss1size[1]
    dss2=frebin(dss2, xdss1size,ydss1size,/total)


;
;   If image size is more than 5% larger than BL_SIZE, blink
;   four quadrants separately of BL_SIZE each
;
    imgpix = fix(BL_SIZE * 60. / DSS1_RESOL)+1 ; Nbr pixels for BL_SIZE
    if (xdss1size LT 1.05 * imgpix) then nquad = 1 $
    else nquad = 4

  for nq = 0, nquad-1 do begin  ; Process each quadrant

    if (nquad EQ 1) then begin
       img1 = dss1
       img2 = dss2
       curstar = starid + '   '
    endif else if (nq EQ 0) then begin
       img1 = dss1(0:imgpix-1, 0:imgpix-1)
       img2 = dss2(0:imgpix-1, 0:imgpix-1)
       curstar = starid + ' ll'
    endif else if (nq EQ 1) then begin
       img1 = dss1(xdss1size-1-imgpix+1:xdss1size-1, 0:imgpix-1)
       img2 = dss2(xdss1size-1-imgpix+1:xdss1size-1, 0:imgpix-1)
       curstar = starid + ' lr'
    endif else if (nq EQ 2) then begin
       img1 = dss1(xdss1size-1-imgpix+1:xdss1size-1, $
                   xdss1size-1-imgpix+1:xdss1size-1)
       img2 = dss2(xdss1size-1-imgpix+1:xdss1size-1, $
                   xdss1size-1-imgpix+1:xdss1size-1)
       curstar = starid + ' ur'
    endif else begin
       img1 = dss1(0:imgpix-1, xdss1size-1-imgpix+1:xdss1size-1)
       img2 = dss2(0:imgpix-1, xdss1size-1-imgpix+1:xdss1size-1)
       curstar = starid + ' ul'
    endelse

    xxtitle='  Object '+ curstar
    title1='Epoch='+string(epoch1[0], format='(A10)')+xxtitle
    title2='Epoch='+string(epoch2[0], format='(A10)')+xxtitle

;   Determine sky level & stdev in the fits images
    sky, img1, skymode1, skysig1,/silent
    sky, img2, skymode2, skysig2,/silent

;   Take the sky out of the fits images
    dss1_r1=img1/skymode1
    dss2_r1=img2/skymode2

;   Identify star pixels where flux gt sky + 3*sky sdev
    dss1starpix=where(img1 gt skymode1 + 3.*skysig1)
    dss2starpix=where(img2 gt skymode2 + 3.*skysig2)

;   Normalize total star flux count for both images
    if (dss1starpix(0) NE -1 AND dss2starpix(0) NE -1) then begin
        totaldss1=total(dss1_r1(dss1starpix))
        totaldss2=total(dss2_r1(dss2starpix))
        dss1_r2=dss1_r1
        dss2_r2=dss2_r1*totaldss1/totaldss2
    endif else begin
        dss1_r2=dss1_r1
        dss2_r2=dss2_r1
    endelse

;   Rotate from -10deg to +10deg to find best match
    angle=findgen(81)*0.25-10.0
    diff=fltarr(81)
    for i=0, 80 do begin
```

```
        newdss2=rot(dss2_r2, angle(i), /interp)
        diff(i)=total((dss1_r2-newdss2)^2)
    endfor

;   Fit gaussian & plot angle vs. goodness of fit
    fitted= gaussfit(angle, diff, AA, nterms=6)
    optrot = AA(1)  ; Optimal rotation in degrees
    window, 3,xsize=300, ysize=300
    plot, angle, diff, psym=4,color=0,background=255, $
          title = 'Optimum rotation = ' + string(optrot,format='(F5.2)') + $
                  ' deg',charsize=0.9,xtitle=curstar
    oplot, angle, fitted,color=0

;   Rotate image 2 by optimum angle to maximize fit
    dss2_r3=rot(dss2_r2, optrot,/interp)

;   Plot image difference to identify CPM
    diffim = dss1_r2 - dss2_r3
    window, 2, xsize=400, ysize=400
    tvim, diffim,/noframe, /rct,title=curstar

;   Plot image 1 & 2, and blink on left-click
    window, 0, xsize=600, ysize=600
    tvim, dss1_r2, /rct,/noframe, title=title1
    xyouts,-40,360,string(format='("Processing ",I3," of ",I3)',curnbr,nproc)
    xyouts,100,-10,'L-Click on image to blink'
    xyouts,100,-20,'Use subtracted image on left & blinking to ID CPM comps'
    xyouts,100,-30,'R-Click on image when done, to capture companion info'
    cursor, readx, ready,3

;
;   If repeatedly blinked, stop on a alternating images after each
;   click. This allows the user to inspect each image closely.
;
    swap = 'n'
    while (!mouse.button eq 1) do begin
       for btimes = 0,14 do begin; blink 15 times for every click
           tvim, dss1_r2, /rct, /noframe, title=title1
           wait, 0.1
           tvim, dss2_r3, /rct, /noframe, title=title2
           wait, 0.1
       endfor
       if (swap EQ 'y') then begin
          tvim, dss1_r2, /rct, /noframe, title=title1
          swap = 'n'
       endif else swap = 'y'
       cursor, readx, ready, 3
    endwhile

;   Collect positions of candidate companions, if any:
;   If primary has no detectable PM, R-click with x & y < 0
;   If primary's PM is marginal, R-click with x > 0 and y < 0
;   If primary's PM is detectable, but no CPM candidate detected,
;   R-click with x < 0 and y > 0
;   If CPM candidates exist, L-click on the primary star, then L-click
;   on every candidate companion.  Then, R-click anywhere when done.

    tvim, dss2_r2, /rct, /noframe, title=title2 ; Display unrot epoch-2
    xyouts,-40,360,string(format='("Processing ",I3," of ",I3)',curnbr,nproc)
    xyouts,-40,-15,'No Pri PM'
    xyouts,-40,-25,'Rclk HERE'
    xyouts,-40,0,'__________'
    xyouts,0,-10,'|',charsize=1.2
    xyouts,0,-17,'|',charsize=1.2
    xyouts,0,-24,'|',charsize=1.2
    xyouts,0,-31,'|',charsize=1.2
    xyouts,0,-38,'|',charsize=1.2
    xyouts,50,-15,'Marginal Primary PM'
    xyouts,50,-25,'   R-Click HERE'
    xyouts,-40,175,'No CPM'
    xyouts,-40,165,'companion'
    xyouts,-40,155,'Rclk HERE'
    xyouts,-40,300,'Can''t proc'
    xyouts,-40,290,'img,R-Clk'
    xyouts,-40,280,'on img-->'
    xyouts,175,-10,'CPM candidate companions exist:'
    xyouts,175,-20,'First, L-Click on primary, then on each candidate'
    xyouts,175,-30,'Finally, R-Click anywhere on image'
    cursor, readx, ready, 3  ; skip or capture primary's position
```

```
    if (!mouse.button EQ 1) then begin ; L-click = capture prim & sec pos

       primx = readx
       primy = ready
       cursor, readx, ready, 3  ; skip or capture primary’s position
       if (!mouse.button NE 1) then begin
        print,format=’(A22,A12,"  ",F7.2,"  Prim selected, but no comp!")’, $
                 dt,curstar,optrot
        if (KEYWORD_SET(outf)) then $
            printf,2,format=’(A22,A12,"  ",F7.2,"  Prim selected, but no comp!")’, $
                 dt,curstar,optrot
        endif
        while (!mouse.button eq 1) do begin ; capture candidate positions
           candx = readx
           candy = ready
           nsdist = (candy - primy) * pltscl * ypixsz ; N-S sep in arcsec
           ewdist = (primx - candx) * pltscl * xpixsz ; E-W sep in arcsec
           sep = sqrt(ewdist^2+nsdist^2)  ; Sep in arcsec
           if (ewdist EQ 0. AND nsdist GE 0.) then pa = 0.        $
           else if (ewdist EQ 0. AND nsdist LT 0.) then pa = 180. $
           else if (ewdist GE 0. AND nsdist EQ 0.) then pa = 90.  $
           else if (ewdist LT 0. AND nsdist EQ 0.) then pa = 270. $
           else if (ewdist GT 0. AND nsdist GT 0.) then $
                    pa = atan(ewdist/nsdist)*180./!pi             $
           else if (ewdist GT 0. AND nsdist LT 0.) then $
                    pa = atan(ewdist/nsdist)*180./!pi + 180.      $
           else if (ewdist LT 0. AND nsdist LT 0.) then $
                    pa = atan(ewdist/nsdist)*180./!pi + 180.      $
           else if (ewdist LT 0. AND nsdist GT 0.) then $
                    pa = atan(ewdist/nsdist)*180./!pi + 360.
           print,format=’(A22,A12,"  ",F7.2,5F8.2,F7.1)’,dt,curstar,$
                 optrot,primx,primy,candx,candy,sep,pa
           if (KEYWORD_SET(outf)) then $
             printf,2,format=’(A22,A12,"  ",F7.2,5F8.2,F7.1)’,dt,curstar,$
                 optrot, primx,primy,candx,candy,sep,pa
           cursor, readx, ready, 3  ; skip or capture next candidate pos
       endwhile

    endif else begin          ; write no PM or no CPM candidate record

       if (readx LT 0. AND ready LT 0.) then begin

          print,format=’(A22,A12,"  ",F7.2,"  No PM for primary detected")’ $
                   ,dt,curstar,optrot
          if (KEYWORD_SET(outf)) then $
            printf,2,format=’(A22,A12,"  ",F7.2,"  No PM for primary detected")’ $
                   ,dt,curstar,optrot

       endif else if (readx GT 0. AND ready LT 0.) then begin

          print,format=’(A22,A12,"  ",F7.2,"  Marginal PM for primary, no CPM candidate found")’,dt,
curstar,optrot
          if (KEYWORD_SET(outf)) then $
             printf,2,format=’(A22,A12,"  ",F7.2,"  Marginal PM for primary, no CPM candidate found"
)’,dt,curstar,optrot

       endif else if (readx LT 0. AND ready GT 0.) then begin

          print,format=’(A22,A12,"  ",F7.2,"  Primary PM detected, but no CPM candidate found")’,dt,
curstar,optrot
          if (KEYWORD_SET(outf)) then $
              printf,2,format=’(A22,A12,"  ",F7.2,"  Primary PM detected, but no CPM candidate found
")’,dt,curstar,optrot

       endif else begin
          print,format=’(A22,A12,"  ",F7.2,"  Error in image! Cannot process")’                  ,d
t,curstar,optrot
          if (KEYWORD_SET(outf)) then $
              printf,2,format=’(A22,A12,"  ",F7.2,"  Error in image! Cannot process")’
     ,dt,curstar,optrot

      endelse
  endelse


 endfor

endfor
```

```
close,1
close,2
spawn,'rm -f ./fitsblink.in'
if (KEYWORD_SET(outf)) then spawn,'cat ./temp.out >> ' + OUTFILE
spawn,'rm -f ./temp.out'

end
```

C.5 Deriving a Visual Orbit From Interferometric Visibilities

C.5.1 Deriving the Best-fit Orbit

```
pro OrbFit, dir, nmiter, OUTF=outf, WRITECS=writecs, VSQ=vsq, Csma=csma

;*************************************************************************
;  CHARA Data Reduction  - Fit observed visibilities to visual orbit       *
;                                                                         *
;  Fit the observed visibilities to a visual orbit to obtain orbital      *
;  parameters. This version does brute-force fitting, similar to          *
;  the MathCAD ORBGRID code.                                              *
;                                                                         *
;  Input:  Paramaters:                                                    *
;            dir        - Directory name of star (e.g. hd008997)          *
;            nmiter     - Nbr of million iterations to try                *
;            /OUTF      - Write results and plot data into utput files    *
;                         if this parameter is set.  Else, write and      *
;                         plot on the screen.                             *
;            /WRITECS   - If set, write CHI-SQ values within 10 of the    *
;                         current minimum value into an output file       *
;                         along with all parameter values for each        *
;                         iteration.  This is used to create 1-D          *
;                         projections of CHI-SQ change for each parameter *
;                         to determine the -, 2, 3 sigma errors.          *
;            /VSQ       - If set, work with V-squared values & error,     *
;                         If not, work with V values and error.           *
;            /CSMA      - If set, constrain angular sma based on          *
;                         asini, plx, and incl                            *
;                         If not, vary asma as a free parameter.          *
;  Input:  Input file with calibrated visibilities (OrbCalV.inp)          *
;            Space-delimited columns are:                                 *
;               Epoch of observation (same unit as T0 - MJD/JD/HJD)       *
;               Baseline (m)                                              *
;               Baseline angle (degrees)                                  *
;               Visibility (Calibrated)                                   *
;               Visibility error                                          *
;               Wavelength of observation (microns)                       *
;            To have the program ignore a data line, place a semicolon(;)  *
;            in the first column                                          *
;          Input file with ranges of orbital elements (OrbEleM.inp)       *
;            First row is column headings (ignored by the program)        *
;            Columns are:                                                 *
;              Parameter name (ignored by program)                        *
;              Lower limit for parameter                                  *
;              Upper limit for parameter                                  *
;            The parameters MUST be speficied in the following order      *
;              Period (days)                                              *
;              Eccentricity                                               *
;              Epoch of Periastron (same unit as Epoch - MJD/JD/HJD)      *
;              Argument of periapse (lowercase omega)                     *
;              Semi-major axis (mas)                                      *
;              Inclination (deg)                                          *
;              Longitude of ascending node (capital OMEGA)                *
;              Delta-mag (mag)                                            *
;              Primary's angular diameter (mas)                           *
;              Secondary's angular diameter (mas)                         *
;            For each parameter, specify a range of valid values          *
;            and an increment value.  If the lower and upper limits       *
;            are equal, the parameter is fixed at the lower limit.        *
;                                                                         *
;                                                                         *
;  Original Version: Deepak Raghavan    March 26, 2007                    *
;                                                                         *
;  Modifications:                                                         *
;                                                                         *
;                                                                         *
;*************************************************************************

;
;  Read input parameters
;

COMMON FUNC_ARGS, obsepoch, base, bang, wvlth, vsqf

parname = ["Period ", "Ecc    ", "T0     ", "l-omega", "a      ", $
           "i      ", "C-OMEGA", "d-mag  ", "Prim-D ", "Sec-D  "]

if (N_PARAMS() EQ 0) then begin  ; set default parameter values
   nmiter = 1
endif

openr,1, '~/idl/thesis/vbo_data/' + dir + '/OrbCalV.inp'
```

```
inp = ' '
inpdat = dblarr(5)
maxdata = 1000  ; maximum data points for visib
obsepoch = dblarr(maxdata)
base = dblarr(maxdata)  ; baseline (m)
bang = dblarr(maxdata)  ; baseline orientation angle (deg)
v = dblarr(maxdata)     ; calibrated visib
verr = dblarr(maxdata)  ; visib error
wvlth = dblarr(maxdata) ; wavelength of observation (microns)
i = -1

while (NOT EOF(1)) do begin

      readf,1,inp
      if (STRMID(inp,0,1) NE ";") then begin
          inpdat = STRSPLIT(inp, ' ', /extract)
          i = i + 1
          obsepoch(i) = inpdat(0)
          base(i) = inpdat(1)
          bang(i) = inpdat(2)
          v(i) = inpdat(3)
          verr(i) = inpdat(4)
          wvlth(i) = inpdat(5)
      endif

endwhile
close,1

vsqf = 'n'
if KEYWORD_SET(vsq) then begin  ;  Convert to V-squared values!
   verr = 2*v*verr
   v = v^2
   vsqf = 'y'
endif

;  Trim arrays to actual number of data elements
nv = i
obsepoch = obsepoch(0:nv)
base = base(0:nv)
bang = bang(0:nv)
v = v(0:nv)
verr = verr(0:nv)
wvlth = wvlth(0:nv)

;
;  Read Orbital element parameters
;

;
;  Initialize physical limits for each parameter
;
npar = 10  ; max possible number of free parameters

if KEYWORD_SET(outf) then begin
   openw, 2, '~/idl/thesis/vbo_data/' + dir + '/OrbFitR.tmp'
   printf,2, ' '
   printf,2, format='(3A)', $
   '************************  ', SYSTIME(), '  ************************'
   printf,2, ' '
endif

openr, 1, '~/idl/thesis/vbo_data/' + dir + '/OrbEleR.inp'
readf, 1, inp  ; Read and ignore header line

inpdat = strarr(4)
i = -1
lowlim = dblarr(npar)
upplim = dblarr(npar)

for i = 0, npar-1 do begin

      readf,1,inp
      inpdat = STRSPLIT(inp, ' ', /extract)
      lowlim(i) = DOUBLE(inpdat(1))
      upplim(i) = DOUBLE(inpdat(2))

endfor
```

```
close,1


totiter = 1.d * nmiter * 1.0e6

print, format='("Total iterations = ", I10, "  started ", 1A)', $
       totiter, SYSTIME()
if KEYWORD_SET(outf) then printf, $
   2, format='("Total iterations = ", I10, "  Nbr visib points = ", I3)', $
       totiter, nv + 1
begt = SYSTIME(1) ; retrieve systime in seconds
begtj = SYSTIME(/JULIAN)

;
;  Setup plot to PS, if required
;
if KEYWORD_SET(outf) then begin
   set_plot,'ps'
   dt = SYSTIME()
   work = STRSPLIT(dt, ' ', /EXTRACT)
   hms = STRSPLIT(work(3), ':', /EXTRACT)
   plotfn = string(format='("~/idl/thesis/vbo_data/",1A,"/OrbFitR_", I4, 2A, "_", 2A, ".ps")', $
            dir, work(4), $
            work(1), strmid(string(format='(I3)', work(2)+100),1,2), $
            hms(0), hms(1))
   device,filename=plotfn, /portrait
endif

if KEYWORD_SET(writecs) then $
   openw, 3, '~/idl/thesis/vbo_data/' + dir + '/OrbFitR.csq'

parm = dblarr(npar)          ; parameter array
bfparm = dblarr(npar)        ; final best-fit parameters
bfidx = 0l                   ; best-fit index
minchisq = 99999999.9d       ; minimum chisq

iter = -1l
while (iter LT totiter) do begin

     iter = iter + 1l
;
;  Generate random values for each parameter within the ranges specified
;
     for ir = 0, npar-1 do begin
         if (lowlim(ir) EQ upplim(ir)) then begin  ; Constant parms
            parm(ir) = lowlim(ir)
         endif else begin
            parm(ir) = lowlim(ir) + $
                       (upplim(ir)-lowlim(ir))* double(RANDOMU(seed))
         endelse
     endfor

;    DR: 3/27/2008
;    Enhancements, per conversation with Latham & Torres
;    a is not a free parameter.  It can be computed using asini from
;    spectroscopy, and i assumed here.  Errors in parallax and asini
;    induce a spread in a values, so process multiple a values.

;  Print progress message only once for iter loop
   piter = 'y'

   if (KEYWORD_SET(csma)) then $
      CalcSma, dir, parm(5), asma, easma, niter $
   else niter = 1

   for ii = 1, niter do begin  ; Process niter values for sma

;     Pick a random value of sma within its 1-sigma error
      if (KEYWORD_SET(csma)) then $
          parm(4) = (asma - easma) + 2.d * easma * double(RANDOMU(seed))

      modelv = calcVis(obsepoch, parm)
      residv = v-modelv
      chisq = TOTAL((residv/verr)^2)
;     Save current data if it is minimum chi-sq
      if (chisq LT minchisq) then begin
         minchisq = chisq
         bfparm = parm
         bfidx = iter
```

```
     endif

;     If chisq is within 10 of the current minimum,
;     write details of current iteration to an output
;     file.  This is used by a subsequent program to
;     create 1-D projections of chi-sq for each
;     parameter to get 1, 2, 3 signam errors
      if (KEYWORD_SET(writecs) AND (chisq LT minchisq + 10.)) $
      then begin
         printf, 3, format='(10F17.9, F10.2)', parm, chisq
      endif

;     Print progress message for long runs (> 10,000 iterations)
      if ((piter EQ 'y') AND (totiter GT 10000.0d) AND $
         (LONG((iter*10/totiter)) NE $
         LONG(((iter-1)*10/totiter)))) then begin
         piter = 'n'
         curt = SYSTIME(1) ; retrieve systime in seconds
         projcmp = SIXTY(((begtj+1.d*totiter/iter*(curt-begt)/ $
                   86400.d + 0.5d) MOD 1.d)*24.d)
         print, format='(I3, "% done in ", I2,2(":",I2),                                        ", p
rojected completion at ", I2, 2(":",I2),                                    ", Min chi-sq = ", F6.1)
', $
                iter*100./totiter, SIXTY((curt-begt)/3600.), $
                projcmp, minchisq
      endif

   endfor

endwhile                             ; end of iterations loop

if KEYWORD_SET(writecs) then close, 3

curt = SYSTIME(1) ; retrieve systime in seconds
print, format='(I3, "% done in ", I2,2(":",I2))', $
                100., SIXTY((curt-begt)/3600.)
if KEYWORD_SET(outf) then printf, $
   2, format='("Job completed in ", I2,2(":",I2), ".  Results:")', $
                SIXTY((curt-begt)/3600.)

print, "Results:"
print, format='("Min chisq = ",F9.2, " at index ", I10)', minchisq, bfidx
print, 'Best-fit parameters'

for ip = 0, npar-1 do begin
    if (lowlim(ip) EQ upplim(ip)) then lim = 'f' $
    else if (bfparm(ip) EQ lowlim(ip)) then lim = '<' $
    else if (bfparm(ip) EQ upplim(ip)) then lim = '>' else lim = ' '
    print, format='(A7, "[", 2F17.9, " ] = ", F17.9, 2X, A1)', $
       parname(ip), lowlim(ip), upplim(ip), bfparm(ip), lim
endfor

if KEYWORD_SET(outf) then begin

   printf,2, format='("Min chisq = ",F9.2, " at index ", I10)', $
             minchisq, bfidx
   printf,2, 'Parameter     Lower-Limit      Upper-Limit        Best-Fit-Value  L'
   for ip = 0, npar-1 do begin
      if (lowlim(ip) EQ upplim(ip)) then lim = 'f' $
      else if ((bfparm(ip) - lowlim(ip)) LT (upplim(ip)-lowlim(ip))*0.1) then $
              lim = '<' $
      else if ((upplim(ip) - bfparm(ip)) LT (upplim(ip)-lowlim(ip))*0.1) then $
              lim = '>' else lim = ' '
      printf,2, format='(A7, "[", 2F17.9, " ] = ", F17.9, 2X, A1)', $
             parname(ip), lowlim(ip), upplim(ip), bfparm(ip), lim
   endfor

   close, 2
   spawn, 'cat ~/idl/thesis/vbo_data/' + dir + '/OrbFitR.tmp >> ~/idl/thesis/vbo_data/' + dir + '/Or
bFitR.results'
   spawn, 'rm -f ~/idl/thesis/vbo_data/' + dir + '/OrbFitR.tmp'

endif


;
;  Compute orbital phase and plot data points and best-fit solution
;
T0 = bfparm(2)
```

```
Per = bfparm(0)
orbphs = dblarr(nv+1) ; Define orbphs as same size as epoch
for i = 0, nv do begin
    if (obsepoch(i) GE T0) then orbphs(i) = ((obsepoch(i)-T0) MOD Per) / Per $
    else orbphs(i) = 1. + (((obsepoch(i) - T0) MOD Per) / Per)
endfor
if (KEYWORD_SET(vsq)) then yts = '^2'  else yts = ' '
if (NOT KEYWORD_SET(outf)) then WINDOW, 1, RETAIN=2
plot, [0],[0],xrange=[-0.05,1.05], yrange=[0.,1.2], psym=3, $
      xtitle = 'Orbital Phase', ytitle = 'Calibrated Visibility (V)'+yts, $
      charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4
;
;  IDL OPLOTERR does not accept THICK parameter, so manually plot
;  values and error bars in thick=4
;
;oploterr, orbphs, v, verr, 1, thick=4
oplot, orbphs, v, psym=1, thick=4
for iv = 0, nv do begin
    oplot, [orbphs(iv), orbphs(iv)], [v(iv)-verr(iv), v(iv)+verr(iv)], $
           linestyle=0, thick=4
endfor

modelv = calcVis(obsepoch, bfparm)
oplot, orbphs, modelv, psym=4, thick=4


;
;  Plot Baseline vs. Visib Curve
;
if (NOT KEYWORD_SET(outf)) then WINDOW, 2, RETAIN=2
plot,[-1],[-1], psym=3, $
     xrange=[fix(min(base)-2),fix(max(base)+2)], $
     yrange = [0.,1.2], xtitle = 'Baseline (meters)', $
     ytitle = 'Calibrated Visibility', $
     charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4
;
;  IDL OPLOTERR does not accept THICK parameter, so manually plot
;  values and error bars in thick=4
;
;oploterr, base, v, verr, 1
oplot, base, v, psym=1, thick=4
for iv = 0, nv do begin
    oplot, [base(iv), base(iv)], [v(iv)-verr(iv), v(iv)+verr(iv)], $
           linestyle=0, thick=4
endfor
oplot, base, modelv, psym=4, thick=4


;
;  Print Each obs, with a extra gap separating each night
;
count = 1
countv = INTARR(nv+1)
countv(0) = count
for iv = 1, nv do begin
    if (fix(obsepoch(iv)) EQ fix(obsepoch(iv-1))) then $ ; same night
       count = count + 1 $ ; increment count by 1
    else  $  ; different night
       count = count + 2  ; insert night gap in data
    countv(iv) = count
endfor

if (NOT KEYWORD_SET(outf)) then WINDOW, 3, RETAIN=2
plot,[-1],[-1], psym=3, $
     xrange=[0,count+1], $
     yrange = [0.,1.2], xtitle = 'Observation', $
     ytitle = 'Calibrated Visibility', $
     charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4
;
;  IDL OPLOTERR does not accept THICK parameter, so manually plot
;  values and error bars in thick=4
;
;oploterr, base, v, verr, 1
oplot, countv, v, psym=1, thick=4
for iv = 0, nv do begin
    oplot, [countv(iv), countv(iv)], [v(iv)-verr(iv), v(iv)+verr(iv)], $
           linestyle=0, thick=4
endfor
oplot, countv, modelv, psym=4, thick=4
```

```
;
;  Print visib values in detail file
;
if KEYWORD_SET(outf) then begin
   openw, 3, '~/idl/thesis/vbo_data/' + dir + '/OrbFitR.visib.fit'
   printf,3, format='(1A)', SYSTIME()
   printf,3, format='(5x,"HJD",7x,"Obs V",1A," Err-V","  Calc V",1A,"   O-C")',yts,yts
   for i = 0, nv do begin
     printf, 3, format='(F12.5, F8.3, F8.3, F8.3, F8.3)', $
                obsepoch(i), v(i), verr(i), modelv(i), v(i)-modelv(i)
   endfor
   close, 3
endif

if KEYWORD_SET(outf) then begin
   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
endif


return
END


pro CalcSma, hdid, incl, angsma, eangsma, niter

;  For given incl (current iteration value of incl in deg),
;  use asini from spectroscopy and parallax from Hipparcos or other
;  sources to compute & return angular sma and its 1-sigma error in mas.
;  Return an "approriate" nbr of tries of sma within 1-sigma error
;  (see calc below for what is "appropriate")

;  Parameters for the stars from spectroscopic orbit and other refs
;  All spectroscopic elements are from CfA orbits
;  Plx for 146361 is from Les1999, and for all others are from van Leeuwen 2007
thd = ['hd008997', 'hd045088', 'hd146361', 'hd223778']
tplx  = [42.13, 67.89, 43.93, 91.82]  ; mas
teplx = [00.68, 01.53, 00.10, 00.30]  ; mas
tasini  = [18.74, 16.849, 2.8098, 14.622]  ; R_sun from CfA orbit
teasini = [00.11, 00.057, 0.0093,  0.053]  ; R_sun from CfA orbit

fd = where(thd EQ hdid)
if (fd(0) EQ -1) then begin
   print, 'HD ID not found! ', hdid
   incl  = -1.
   eincl = -1.
   niter = -1.
   RETURN
endif else fdi = fd(0)

asini  = tasini(fdi) * 696000./1.496e8  ; Convert to AU
easini = teasini(fdi) * 696000./1.496e8 ; Convert to AU
plx = tplx(fdi)
eplx  = teplx(fdi)

sma = asini / sin(incl*!pi/180.)
esma = SQRT( (easini/sin(incl*!pi/180.))^2. )

angsma = sma * plx
eangsma = angsma * SQRT( (esma/sma)^2. + (eplx/plx)^2. )

;  Do 1 iteration per 0.01 mas uncertainty in angsma.
;  Limit iterations to between 3 and 15
niter = fix(eangsma/0.01)
if (niter LT 3) then niter = 3
if (niter GT 15) then niter = 15

return
END

@~/idl/thesis/CalcVis
```

C.5.2 Example Input File of Calibrated Visibilities

```
;    HJD          Baseline     Base-orient    Visib        Visib-err   Wavelength
; UT 2007-05-17 data
   54237.76327   322.1841535   38.90860753  0.8640769114 0.08580654039   2.1329
   54237.77388   324.5476995   37.30277017  0.9091188593   0.106622512   2.1329
   54237.78419   326.4113232   35.67037403  0.7364975443 0.06168599425   2.1329
   54237.79557   328.0124214   33.78930955  0.7020072262 0.06269439484   2.1329
   54237.80566   329.0755172   32.04316448  0.5845545093 0.05771936068   2.1329
   54237.81631   329.8684988   30.13042126  0.6523913486 0.07643914754   2.1329
   54237.83333   330.540187    26.92415368  0.4680483653 0.05339319801   2.1329
   54237.93189   328.3259477    5.313527934 0.8332661835 0.04919897218   2.1329
   54237.94172   328.1780545    2.98267306  0.774508627  0.05928058711   2.1329
   54237.95385   328.1087726    0.09088828  0.6724026543 0.03818548611   2.1329
   54237.98020   328.4001867  173.8252467   0.2436991552 0.01545608878   2.1329
; UT 2007-05-27 data
   54247.70094   267.8789627   36.65248893  0.8584099682    0.11275264   2.1329
   54247.71566   271.0695809   34.63715219  0.8881816548  0.0796278443   2.1329
   54247.72925   273.4224039   32.64404675  0.8243610105 0.08334095568   2.1329
   54247.74400   275.3865649   30.34974599  0.6693624858 0.09335511181   2.1329
   54247.76088   276.9845969   27.54552975  0.4352274163  0.0577530859   2.1329
; UT 2007-05-29 data
   54249.71443   271.8639639   34.02704177  0.5890979542  0.0525760834   2.1329
   54249.72550   273.6829955   32.38170559  0.5703079435 0.05386102256   2.1329
   54249.73937   275.4838152   30.2106718   0.5748088173 0.06444664595   2.1329
   54249.75079   276.6128202   28.32720157  0.5939382742 0.06269114484   2.1329
   54249.77217   277.9874522   24.59837625  0.3912264245 0.05944668181   2.1329
; UT 2007-07-29 data
   54310.71647   328.6495782   8.516645449  0.6157056247 0.06179587933   2.1329
   54310.72609   328.4076091   6.258141671  0.4050823413 0.05033409499   2.1329
   54310.77554   328.3412799   174.4944247  0.4771855878 0.04980552717   2.1329
   54310.78593   328.5842383   172.0420132  0.5583759033 0.05400055664   2.1329
   54310.79650   328.897506    169.5794852  0.8701816929 0.09978546524   2.1329
```

C.5.3 Example Input File of Orbital Elements

```
Element                  Lower_Limit       Upper_Limit
Period_(P,days)           1.139791343        1.139791503
Eccentricity_(e)          0.000              0.000
Epoch_of_node(T,HJD)      50127.04835        50127.04875
l-omega_(deg)             0.0                0.0
semi-major_axis_(a,mas)   1.19               1.27
inclination_(i,deg)       27.0               29.0
C-OMEGA_(deg)             206.0              210.5
del-mag_(mag)             0.0                0.7
Angular_dia_prim_(mas)    0.45               0.55
Angular_dia_sec_(mas)     0.40               0.50
```

C.5.4 Calculating Interferometric Visibility for Given Parameters

```
FUNCTION calcVis, epoch, P, DEBUG = debug
;*********************************************************************
;  FUNCTION calcVis - Calculate visibility for a given t (independent var) *
;                    and input parameters as below:                  *
;                                                                    *
;     epoch = Epoch of observation (same unit as T0 - MJD/JD/HJD)         *
;     P(0)  = Period (days)                                          *
;     P(1)  = Eccentricity                                           *
;     P(2)  = Epoch of Periastron (same unit as epoch - MJD/JD/HJD)       *
;     P(3)  = Argument of periapse (lowercase omega)                 *
;     P(4)  = Semi-major axis (mas)                                  *
;     P(5)  = Inclination (deg)                                      *
;     P(6)  = Longitude of ascending node (capital OMEGA)            *
;     P(7)  = Delta-mag (mag)                                        *
;     P(8)  = Primary's angular diameter (mas)                       *
;     P(9)  = Secondary's angular diameter (mas)                     *
;                                                                    *
;     In addition to the above parameters, this function requires the      *
;     following parameters passed via the COMMON block:              *
;     COMMON FUNC_ARGS, obsepoch, base, bang, wvlth, vsqf            *
;       obsepoch = array of epochs of observations                   *
;       base = array of baselines (m) of observations                *
;       bang = array of baseline orientations (deg) of observations  *
;       wvlth = Wavelength (microns) of observation                  *
;       vsqf = If set to 'y', return V^2, else return V              *
;                                                                    *
;*********************************************************************

COMMON FUNC_ARGS, obsepoch, base, bang, wvlth, vsqf

;
;  Fitted parameters
;
Per = P(0)
ecc = P(1)
T0 = P(2)
lomega = P(3)
a = P(4)
incl = P(5)
COmega = P(6)
dmag = P(7)
angdiaP = P(8)
angdiaS = P(9)

;
;  Conversion constants
;

d2r = !pi / 180.  ; degrees to radians
r2d = 180./ !pi   ; radians to degrees
m2r = 1.e-3/3600. * d2r  ; mas to radians

;
;  Input epoch could be an array of dates.  Process each element and
;  load results into an array as well
;

nele = SIZE(epoch,/DIMENSIONS)
nele = nele (0)
if (nele EQ 0) then begin
   calcV = 0.d  ; define as scalar
   nele = 1     ; force one iteration of follwoing loop
endif else $
   calcV = dblarr(nele)

for ci = 0, nele-1 do begin

;
;   Lookup baseline and its orientation for current epoch
;

    curt = epoch(ci)
    ti = where(obsepoch EQ curt)
    if (ti EQ -1) then begin
       print, 'Current epoch not found', curt
       ERROR_CODE = -1
       return, 0.
    endif
```

```
    curbase = base(ti)
    curbang = bang(ti)
    curbang = bang(ti)
    curwv = wvlth(ti) / 1000000.d   ; in meters

;
;   Calculate visibilities for the individual stars
;

    besf = !pi * curbase / curwv  ; Besel function factor
    Vprim = 2.d * BESELJ(angdiaP * m2r * besf, 1) / (angdiaP * m2r * besf)
    Vsec = 2.d * BESELJ(angdiaS * m2r * besf, 1) / (angdiaS * m2r * besf)

;
;   CALCULATE ORBITAL PROPERTIES
;

;
;   Mean anomaly
;
    MA = 2*!pi/Per*(curt-T0)
;
;   Eccentric anomaly, solved over 20 iterations
;
    EA = MA + ecc * SIN(MA) + ecc^2 / 2. * SIN(2*MA)  ; Starting value (E3)
    for i = 1, 20 do EA = MA + ecc * SIN(EA)
;
;   True anomaly
;
    TA = 2.d*ATAN(SQRT((1.+ecc)/(1.-ecc))*TAN(EA/2.d))
;
;   Position vector magnitude (radius)
;
    posr = a * (1. - ecc * COS(EA))
    rho = posr * SQRT(1 - SIN(TA+lomega*d2r)^2.*SIN(incl*d2r)^2.)
;
;   Angle of position vector (theta)
;
    ttemp = ABS(ATAN(TAN(TA+lomega*d2r)*COS(incl*d2r)))
    if (SIN(TA+lomega*d2r) GE 0. AND COS(TA+lomega*d2r) GE 0.) then $
       tmo = ttemp
    if (SIN(TA+lomega*d2r) GE 0. AND COS(TA+lomega*d2r) LT 0.) then $
       tmo = !pi - ttemp
    if (SIN(TA+lomega*d2r) LT 0. AND COS(TA+lomega*d2r) GE 0.) then $
       tmo = 2. * !pi - ttemp
    if (SIN(TA+lomega*d2r) LT 0. AND COS(TA+lomega*d2r) LT 0.) then $
       tmo = !pi + ttemp
    if (COS(incl*d2r) GE 0.) then theta = COmega + tmo * r2d $
    else theta = COmega - tmo * r2d
    if (theta GT 360.) then theta = theta - 360.

    beta = 10.^(0.4*dmag)

    if (vsqf EQ 'y') then $ ;  Return V-squared values
       calcV(ci) = 1./(1. + beta)^2 * (beta^2*Vprim^2 + Vsec^2 + $
                 2*beta*Vprim*Vsec* $
             COS(2.*!pi*curbase/curwv*rho*m2r*ABS(COS((theta-curbang)*d2r)))) $
    else $                   ; Return V
       calcV(ci) = 1./(1. + beta) * SQRT(beta^2*Vprim^2 + Vsec^2 + $
                 2*beta*Vprim*Vsec* $
             COS(2.*!pi*curbase/curwv*rho*m2r*ABS(COS((theta-curbang)*d2r))))

;   Print details if called in debug mode
    if KEYWORD_SET(debug) then begin
        print, format='("P, e, T0, lo, a: ", 5F12.4)',P(0:4)
        print, format='("i, CO, dm, diap, dias: ", 5F12.4)',P(5:9)
        print, format='("t, Base, B-ang: ", 3F16.6)', $
                         epoch, curbase, curbang
        print, format='("wavelth: ", E14.6)', curwv
        print, format='("Visib_P, Visib_S: ", 2F14.6)', Vprim, Vsec
        print, format='("MA, EA, TA, TA+2pi: ", 4F16.6)', MA, EA, TA, TA+2*!pi
        print, format='("Posr, rho, theta, beta, TMO: ", 5F12.6)', $
                         posr, rho, theta, beta, tmo
        print, format='("Terms of Visib eq: ", 5F10.6)', $
             beta^2*Vprim^2, Vsec^2, 2*beta*Vprim*Vsec, $
             COS(2.*!pi*curbase/curwv*rho*m2r*ABS(COS((theta-curbang)*d2r))), $
             ABS(COS((theta-curbang)*d2r))
        print, format='("Calculated V = ", F6.3)', calcV
        stop
```

```
    endif


endfor

return, calcV
END
```

C.5.5 Estimating Parameter Uncertainties

```
pro OrbErr, dir, mincs, SEPPS=sepps

;*************************************************************************
;  CHARA Data Reduction  - Explore parameter space to establish 1, 2, 3    *
;                          sigma errors for each parameter                 *
;                                                                          *
;  Read the parameter/chi-sq data points generated by OrbitFitR.pro        *
;  and create 1-D projections for each parameter. Fit the lower envelope   *
;  of each projection with a curve to get the 1, 2, 3 sigma errors.        *
;                                                                          *
;  Input:  Paramaters:                                                     *
;            mincs   Minimum chi-sq value for these data points from       *
;                    OrbFitR.pro                                           *
;            /SEPPS  If set, generate separate PS file for each param      *
;  Input:  Input file with values of each parameter and corr chi-sq        *
;            (OrbFitR.csq)                                                 *
;            Space-delimited columns are:                                  *
;              Period (days)                                               *
;              Eccentricity                                                *
;              Epoch of Periastron (same unit as Epoch - MJD/JD/HJD)       *
;              Argument of periapse (lowercase omega)                      *
;              Semi-major axis (mas)                                       *
;              Inclination (deg)                                           *
;              Longitude of ascending node (capital OMEGA)                 *
;              Delta-mag (mag)                                             *
;              Primary's angular diameter (mas)                            *
;              Secondary's angular diameter (mas)                          *
;              Chi-square value for current set of parameters              *
;          Input file with ranges of orbital elements (OrbEleR.inp)        *
;            This file is read only to get the limits of each parameter    *
;            in order to set XRANGE for the plots.                         *
;            First row is column headings (ignored by the program)         *
;            Columns are:                                                  *
;              Parameter name (ignored by program)                         *
;              Lower limit for parameter                                   *
;              Upper limit for parameter                                   *
;                                                                          *
;  Output: Plots for each parameter variation for 1, 2, 3 sigma errors     *
;                                                                          *
;  Original Version: Deepak Raghavan    September 10, 2007                 *
;                                                                          *
;  Modifications:                                                          *
;                                                                          *
;                                                                          *
;*************************************************************************


;
;  Initialize constants and arrays
;
npar = 10  ; max possible number of free parameters
parname = ["Period ", "Ecc    ", "T0     ", "!7x!X!N (degrees)", $
           "!7a!X!N (mas)", "i (degrees)", "!7X!X!N (degrees)", $
           "!7D!X!NK' (magnitude)", "!7H!X!Np", "!7H!X!Ns"]


;
;  Read parameter ranges for use in setting XRANGE for plots
;

inp = ' '
openr, 1, '~/idl/thesis/vbo_data/' + dir + '/OrbEleR.inp'
readf, 1, inp  ; Read and ignore header line

inpdat = strarr(4)
i = -1
lowlim = dblarr(npar)
upplim = dblarr(npar)

for i = 0, npar-1 do begin

      readf,1,inp
      inpdat = STRSPLIT(inp, ' ', /extract)
      lowlim(i) = DOUBLE(inpdat(1))
      upplim(i) = DOUBLE(inpdat(2))

endfor

close,1

;
```

```
;  Setup plot file
;

if (NOT KEYWORD_SET(sepps)) then begin ; Combined PS for all params
   set_plot,'ps'
   device,filename="~/idl/thesis/vbo_data/"+dir+"/OrbErrR.ps", /portrait
endif

for ip = 0, npar-1 do begin

    if (lowlim(ip) EQ upplim(ip)) then CONTINUE  ; skip for fixed parameters

    if (KEYWORD_SET(sepps)) then begin ; Separate PS for each param
       set_plot,'ps'
       device,filename=string(format='("~/idl/thesis/vbo_data/",2A,I1,1A)', $
                   dir,"/OrbErrR.",ip,".ps"), $
              /portrait
    endif

;
;  Setup plot area for current parameter
;

    xlow = lowlim(ip)-(upplim(ip)-lowlim(ip))/10.
    xupp = upplim(ip)+(upplim(ip)-lowlim(ip))/10.

    if (ip EQ 0) then $ ; Period axis value format
       plot, [xlow], [mincs-3], xrange=[xlow,xupp], $
             yrange=[mincs-3,mincs+10], psym=3, $
             xtitle = parname(ip), ytitle = '!7v!X!N!U2', $
             charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4, $
             xtickformat='(F8.5)' $
    else if (ip EQ 2) then $  ; T0 axis value format
       plot, [xlow], [mincs-3], xrange=[xlow,xupp], $
             yrange=[mincs-3,mincs+10], psym=3, $
             xtitle = parname(ip), ytitle = '!7v!X!N!U2', $
             charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4, $
             xtickformat='(F9.2)' $
    else $
       plot, [xlow], [mincs-3], xrange=[xlow,xupp], $
             yrange=[mincs-3,mincs+10], psym=3, $
             xtitle = parname(ip), ytitle = '!7v!X!N!U2', $
             charsize=1.2, xthick=3, ythick=3, charthick=4, thick=4

    oplot, [!x.crange(0), !x.crange(1)], [mincs, mincs], linestyle=5, thick=4
    oplot, [!x.crange(0), !x.crange(1)], [mincs+1, mincs+1], $
           linestyle = 5, thick=4
    oplot, [!x.crange(0), !x.crange(1)], [mincs+4, mincs+4], $
           linestyle = 5, thick=4
    oplot, [!x.crange(0), !x.crange(1)], [mincs+9, mincs+9], $
           linestyle = 5, thick=4

;
;   Read parameters & chi-sq values
;

    openr,1, '~/idl/thesis/vbo_data/' + dir + '/OrbFitR.csq'

    inpdat = dblarr(11)
    minchisq = 999999999.9d

    while (NOT EOF(1)) do begin

          readf,1,inpdat
          curpar = inpdat(ip)      ; save current parameter
          curchisq = inpdat(npar)  ; chi-sq is the last column
          if (curchisq LT minchisq) then begin
             minchisq = curchisq
             mincspar = curpar
          endif

          oplot, [curpar], [curchisq], psym=3

    endwhile
    close,1

;    xyouts, !x.crange(0)+(!x.crange(1)-!x.crange(0))/10., mincs-2., $
;            string(format='(A10, " = ", F14.6)', parname(ip), mincspar)
```

```
    if (KEYWORD_SET(sepps)) then begin ; Separate PS for each param
       device,/close   ; close the PS file
       set_plot,'x'    ; revert back to terminal graphics output
    endif


endfor

if (NOT KEYWORD_SET(sepps)) then begin ; Combined PS for all params
   device,/close   ; close the PS file
   set_plot,'x'    ; revert back to terminal graphics output
endif

return
END
```

– D –

Two Suns in the Sky: Stellar Multiplicity in Exoplanet Systems

This chapter reproduces a 2006 Astrophysical Journal publication (Raghavan et al. 2006), which was completed as a part of this thesis effort.

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TWO SUNS IN THE SKY: STELLAR MULTIPLICITY IN EXOPLANET SYSTEMS

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ABSTRACT

We present results of a reconnaissance for stellar companions to all 131 radial velocity–detected candidate extrasolar planetary systems known as of 2005 July 1. Common proper-motion companions were investigated using the multiepoch STScI Digitized Sky Surveys and confirmed by matching the trigonometric parallax distances of the primaries to companion distances estimated photometrically. We also attempt to confirm or refute companions listed in the Washington Double Star Catalog, in the Catalogs of Nearby Stars Series by Gliese and Jahreiß, in *Hipparcos* results, and in Duquennoy & Mayor's radial velocity survey. Our findings indicate that a lower limit of 30 (23%) of the 131 exoplanet systems have stellar companions. We report new stellar companions to HD 38529 and HD 188015 and a new candidate companion to HD 169830. We confirm many previously reported stellar companions, including six stars in five systems, that are recognized for the first time as companions to exoplanet hosts. We have found evidence that 20 entries in the Washington Double Star Catalog are not gravitationally bound companions. At least three (HD 178911, 16 Cyg B, and HD 219449), and possibly five (including HD 41004 and HD 38529), of the exoplanet systems reside in triple-star systems. Three exoplanet systems (GJ 86, HD 41004, and γ Cep) have potentially close-in stellar companions, with planets at roughly Mercury–Mars distances from the host star and stellar companions at projected separations of ~20 AU, similar to the Sun–Uranus distance. Finally, two of the exoplanet systems contain white dwarf companions. This comprehensive assessment of exoplanet systems indicates that solar systems are found in a variety of stellar multiplicity environments—singles, binaries, and triples—and that planets survive the post–main-sequence evolution of companion stars.

Subject headings: binaries: general — planetary systems — surveys

Online material: machine-readable tables

1. INTRODUCTION

The hunt for planets outside our solar system has revealed 161 candidate planets in 137 stellar systems as of 2005 July 1, with 18 of these systems containing multiple planets. After the initial flurry of "hot jupiter" discoveries—primarily a selection effect due to the fact that (1) the nascent effort was biased toward discovery of short-period systems and (2) massive planets induce more readily detected radial velocity variations—it is now believed that the more massive planets preferentially lie farther away from the primary (Udry et al. 2004; Marcy et al. 2005a), perhaps leaving the space closer to the star for the harder to detect terrestrial planets. Through these discoveries, we are now poised to gain a better understanding of the environments of exoplanet systems and compare them to our solar system.

Our effort in this paper is focused on a key parameter of planetary systems: the stellar multiplicity status of exoplanet hosts. We address questions such as the following: (1) Do planets preferentially occur in single-star systems (like ours), or do they commonly occur in multiple-star systems as well? (2) For planets residing in multiple-star systems, how are the planetary orbits related to stellar separations? (3) What observational limits can we place on disk truncations or orbit disruptions in multistar planetary systems? This study contributes to the broader subjects of planetary system formation, evolution, and stability through a better understanding of the environments of exoplanet systems.

Stellar multiplicity among exoplanet systems was first studied by Patience et al. (2002), who looked at the first 11 exoplanet systems discovered and reported two binaries and one triple system. Luhman & Jayawardhana (2002) conducted an adaptive optics (AO) survey looking for stellar and substellar companions to 25 exoplanet hosts and reported null results. More recently, Eggenberger et al. (2004) and Udry et al. (2004) reported 15 exoplanet systems with stellar companions in a comprehensive assessment, and additional companions have been reported for several specific systems (Mugrauer et al. 2004a, 2004b, 2005). Our effort confirms many of these previously reported systems, reports two new companions, identifies an additional candidate, and recognizes, for the first time, one triple and four binary exoplanet systems (these are known stellar

TABLE 1
Exoplanet Systems Searched for Companions

Name (1)	Proper Motion (arcsec yr^{-1}) (2)	Proper Motion (deg) (3)	DSS Images Epoch 1 (4)	DSS Images Epoch 2 (5)	Total μ (arcsec) (6)	μ Observable? (7)	Companions CPM (8)	Companions Other (9)
BD −10 3166	0.183	268.5	1983.29	1992.04	1.602	Yes	...	...
GJ 436	1.211	132.2	1955.28	1996.38	49.770	Yes	...	...
GJ 876	1.174	125.1	1983.76	1989.83	7.116	Yes	...	...
HD 000142	0.577	94.0	1982.87	1996.62	7.933	Yes	...	B
HD 001237	0.438	97.6	1977.77	1997.58	8.676	Yes	...	...
HD 002039	0.080	79.0	1978.82	1997.61	1.503	No	...	...
HD 002638	0.248	205.5	1983.53	1993.85	2.560	Yes	...	...
HD 003651	0.592	231.2	1953.91	1987.65	19.972	Yes	...	...
HD 004203	0.176	134.7	1954.00	1987.65	5.922	Yes	...	...
HD 004208	0.348	64.4	1980.63	1989.74	3.171	No	...	...
HD 006434	0.554	197.8	1976.89	1990.73	7.666	Yes	...	...
HD 008574	0.298	122.1	1949.98	1991.76	12.453	Yes	...	...
HD 008673	0.250	109.8	1954.67	1991.76	9.273	Yes	...	B?
HD 009826	0.418	204.4	1953.71	1989.77	15.073	Yes	B	B
HD 010647	0.198	122.6	1977.92	1997.61	3.898	Yes	...	...
HD 010697	0.115	203.1	1954.89	1986.69	3.657	Yes	...	...
HD 011964	0.441	236.6	1982.63	1991.70	4.003	Yes	B	B
HD 011977	0.105	46.1	1976.67	1987.72	1.160	No	...	...
HD 012661	0.206	211.6	1953.87	1990.87	7.622	No	...	...
HD 013189	0.006	13.3	1954.76	1989.83	0.210	No	...	...
HD 013445	2.193	72.6	1975.85	1988.91	28.646	Yes	...	B
HD 016141	0.464	199.7	1982.79	1997.74	6.937	Yes	...	B?
HD 017051	0.399	56.7	1977.78	1997.81	7.995	Yes	...	...
HD 019994	0.205	109.7	1951.69	1997.84	9.463	Yes	...	B
HD 020367	0.118	241.2	1953.77	1993.72	4.714	Yes	...	...
HD 022049	0.977	277.1	1982.79	1998.97	15.806	Yes	...	...
HD 023079	0.214	244.6	1978.82	1993.96	3.241	Yes	...	...
HD 023596	0.058	68.5	1953.03	1989.76	2.130	No	...	...
HD 027442	0.175	196.0	1983.04	1997.74	2.573	Yes	...	B
HD 027894	0.328	33.8	1983.04	1997.74	4.823	Yes	...	...
HD 028185	0.101	126.7	1982.82	1985.96	0.317	No	...	...
HD 030177	0.067	100.3	1983.04	1997.74	0.985	No	...	...
HD 033636	0.227	127.2	1954.85	1990.81	8.164	Yes	...	...
HD 034445	0.149	184.4	1954.85	1990.82	5.360	Yes	...	...
HD 037124	0.427	190.8	1951.91	1991.80	17.032	Yes	...	...
HD 037605	0.252	167.5	1955.90	1992.06	9.114	Yes	...	...
HD 038529	0.163	209.4	1951.91	1990.87	6.350	Yes	B	...
HD 039091	1.096	16.5	1978.03	1989.99	13.116	Yes	...	...
HD 040979	0.179	148.0	1953.12	1989.83	6.570	Yes	B	B
HD 041004	0.078	327.0	1978.03	1993.96	1.243	Yes	...	B, C
HD 045350	0.069	219.3	1953.19	1986.91	2.326	No	...	...
HD 046375	0.150	130.3	1953.94	1998.88	6.740	Yes	...	B
HD 047536	0.126	59.5	1979.00	1992.99	1.763	Mar	...	...
HD 049674	0.128	164.1	1953.19	1989.86	4.694	Yes	...	...
HD 050499	0.097	314.8	1976.89	1994.21	1.679	No	...	...
HD 050554	0.103	201.2	1956.27	1994.03	3.889	Yes	...	...
HD 052265	0.141	304.8	1983.04	1989.18	0.864	No	...	...
HD 059686	0.087	150.5	1953.02	1989.08	3.137	Mar	...	...
HD 063454	0.045	207.5	1975.94	1992.99	0.767	No	...	...
HD 065216	0.190	320.1	1976.25	1991.13	2.827	No	...	...
HD 068988	0.132	76.1	1954.01	1989.98	4.747	Yes	...	...
HD 070642	0.303	318.1	1976.97	1991.10	4.283	No	...	...
HD 072659	0.150	229.2	1954.97	1992.03	5.559	Yes	...	...
HD 073256	0.192	290.0	1977.22	1991.26	2.697	Mar	...	...
HD 073526	0.173	339.5	1977.06	1991.27	2.459	Mar	...	...
HD 074156	0.202	172.9	1953.02	1991.10	7.692	Yes	...	...
HD 075289	0.229	185.1	1977.06	1991.27	3.255	Yes	...	B
HD 075732	0.539	244.2	1953.94	1998.30	23.908	Yes	B	B
HD 076700	0.308	293.2	1976.26	1991.05	4.558	Yes	...	...
HD 080606	0.047	81.6	1953.13	1995.25	1.979	Yes	B	B
HD 082943	0.174	179.2	1983.36	1987.32	0.689	No	...	...
HD 083443	0.123	169.5	1980.06	1995.09	1.849	No	...	...

TABLE 1—*Continued*

Name (1)	Proper Motion (arcsec yr^{-1}) (2)	Proper Motion (deg) (3)	DSS Images: Epoch 1 (4)	DSS Images: Epoch 2 (5)	Total μ (arcsec) (6)	μ Observable? (7)	Companions: CPM (8)	Companions: Other (9)
HD 088133	0.264	182.8	1955.23	1998.99	11.555	Yes	...	...
HD 089307	0.276	261.8	1950.29	1987.32	10.219	Yes	...	...
HD 089744	0.183	220.9	1953.21	1990.23	6.773	No	...	B
HD 092788	0.223	183.2	1982.37	1991.21	1.971	Yes	...	...
HD 093083	0.177	211.6	1980.21	1995.10	2.636	Yes	...	...
HD 095128	0.321	279.9	1955.22	1998.38	13.855	Yes	...	...
HD 099492	0.755	284.7	1955.29	1996.28	30.944	Yes	A	A
HD 101930	0.348	2.5	1987.20	1992.24	1.754	No	...	...
HD 102117	0.094	222.1	1987.20	1992.24	0.474	No	...	...
HD 104985	0.174	122.1	1955.17	1997.11	7.299	Yes	...	...
HD 106252	0.280	175.1	1955.29	1991.27	10.076	Yes	...	...
HD 108147	0.192	251.5	1987.26	1996.30	1.735	No	...	...
HD 108874	0.157	124.7	1955.39	1991.07	5.602	Yes	...	...
HD 111232	0.116	13.9	1987.08	1996.29	1.067	No	...	B?
HD 114386	0.353	203.0	1975.41	1992.25	5.943	Yes	...	...
HD 114729	0.369	213.2	1978.13	1991.21	4.826	Yes	...	B
HD 114762	0.583	269.8	1950.30	1996.30	26.822	Yes	...	B
HD 114783	0.138	274.0	1956.27	1996.23	5.514	Yes	...	...
HD 117176	0.622	202.2	1955.38	1997.35	26.110	Yes	...	...
HD 117207	0.217	250.7	1975.27	1991.21	3.458	Mar	...	...
HD 117618	0.127	168.6	1975.19	1991.23	2.037	No	...	...
HD 120136	0.483	276.4	1954.25	1992.20	18.328	Yes	...	B
HD 121504	0.264	251.5	1987.26	1994.19	1.828	No	...	...
HD 128311	0.323	140.5	1950.28	1989.25	12.588	Yes	...	...
HD 130322	0.191	222.6	1980.22	1996.37	3.085	Yes	...	...
HD 134987	0.400	86.1	1976.42	1991.50	6.034	Yes	...	...
HD 136118	0.126	280.7	1955.30	1992.41	4.676	Yes	...	...
HD 137759	0.019	334.5	1953.46	1995.15	0.792	No	...	...
HD 141937	0.100	76.1	1976.41	1991.61	1.520	No	...	...
HD 142022	0.339	264.7	1977.63	1996.30	6.329	Yes	B	B
HD 142415	0.153	228.1	1988.30	1992.58	0.654	No	...	...
HD 143761[a]	0.798	194.3	1950.28	1994.37	35.182	Yes	...	...
HD 145675	0.326	156.1	1955.23	1991.43	11.802	Yes	...	...
HD 147513	0.073	87.3	1987.39	1993.25	0.428	No	...	B
HD 149026	0.094	304.7	1954.49	1993.33	3.651	Yes	...	...
HD 150706	0.130	132.6	1955.39	1996.54	5.350	Yes	...	B?
HD 154857	0.103	122.4	1987.30	1993.32	0.621	No	...	...
HD 160691	0.192	184.5	1987.70	1992.58	0.938	No	...	...
HD 162020	0.033	140.2	1987.71	1991.68	0.131	No	...	...
HD 168443	0.242	202.3	1978.65	1988.59	2.406	No	...	...
HD 168746	0.073	197.7	1978.65	1988.59	0.726	No	...	...
HD 169830	0.015	356.8	1987.38	1992.41	0.075	No	...	B?
HD 177830	0.066	218.1	1950.46	1992.42	2.770	No	...	...
HD 178911B	0.203	18.6	1955.39	1992.44	7.523	Yes	A	A, C
HD 179949	0.153	131.6	1987.42	1991.62	0.643	No	...	...
HD 183263	0.038	208.2	1950.61	1992.59	1.595	No	...	...
HD 186427	0.212	219.6	1951.53	1991.53	8.679	Yes	A	A, C
HD 187123	0.189	130.7	1952.54	1992.67	7.583	Yes	...	...
HD 188015	0.106	149.4	1953.53	1992.49	4.130	Yes	B	...
HD 190228	0.126	123.7	1953.53	1992.49	4.910	Yes	...	...
HD 190360	0.861	127.5	1953.53	1992.49	33.549	Yes	B	B
HD 192263	0.270	346.4	1951.58	1988.67	10.013	Yes	...	...
HD 195019	0.354	99.2	1951.52	1990.71	13.874	Yes	...	B
HD 196050	0.201	251.4	1977.61	1991.75	2.842	Mar	...	B
HD 196885	0.096	29.7	1953.68	1987.50	3.246	Yes	...	...
HD 202206	0.126	197.7	1977.55	1991.74	1.788	No	...	...
HD 208487	0.156	139.3	1980.55	1995.63	2.353	Mar	...	...
HD 209458	0.034	122.4	1950.54	1990.73	1.366	No	...	...
HD 210277	0.458	169.2	1979.72	1987.79	3.693	Yes	...	...
HD 213240	0.236	214.9	1980.77	1995.65	3.510	Yes	B	B
HD 216435	0.232	110.6	1980.54	1996.62	3.730	No	...	...
HD 216437	0.085	329.5	1978.82	1996.79	1.527	No	...	...
HD 216770	0.290	127.9	1980.78	1995.79	4.354	Yes	...	...

TABLE 1—*Continued*

Name (1)	Proper Motion (arcsec yr^{-1}) (2)	Proper Motion (deg) (3)	DSS Images Epoch 1 (4)	DSS Images Epoch 2 (5)	Total μ (arcsec) (6)	μ Observable? (7)	Companions CPM (8)	Companions Other (9)
HD 217014	0.217	73.7	1954.59	1990.79	7.856	Yes	...	...
HD 217107	0.017	200.7	1982.80	1991.68	0.151	No	...	B?
HD 219449	0.369	92.6	1983.82	1991.76	2.931	Yes	B	B, C
HD 222404	0.136	339.0	1954.73	1992.76	5.172	Yes	...	B
HD 222582	0.183	232.6	1983.54	1989.83	1.152	Yes	B	B
HD 330075	0.254	248.2	1988.45	1995.25	1.725	No	...	...

Note.—Table 1 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*.
[a] We conclude that this system (ρ CrB) has either a planetary or a stellar companion, but not both. See § 2.3 for more details.

companions, but previously not noted to reside in exoplanet systems).

2. SAMPLE AND COMPANION SEARCH METHODOLOGY

Our sample includes all known exoplanet systems detected by radial velocity techniques as of 2005 July 1. We primarily used the Extrasolar Planets Catalog,[1] maintained by Jean Schneider at the Paris Observatory, to build our sample list for analyses. To ensure completeness, we cross-checked this list with the California & Carnegie Planet Search Catalog.[2] Our sample excludes planets discovered via transits and gravitational lensing, as these systems are very distant, with poor or no parallax and magnitude information for the primaries. In addition, these systems cannot be observed for stellar companions in any meaningful way. We also exclude a radial velocity–detected system, HD 219542, identified by Eggenberger et al. (2004) as an exoplanet system with multiple stars but since confirmed as a false planet detection by its discoverers (Desidera et al. 2004). The final sample comprises 155 planets in 131 systems. This list is included in Table 1 along with companion detection information, as described below.

Several efforts were carried out to gather information on stellar companions to exoplanet stars. To identify known or claimed companions, we checked available sources listing stellar companions: the Washington Double Star Catalog (WDS), the *Hipparcos* Catalog (Perryman et al. 1997), the Catalog of Nearby Stars (CNS; Gliese 1969; Gliese & Jahreiss 1979, 1991), and Duquennoy & Mayor (1991). We also visually inspected the STScI Digitized Sky Survey (DSS) multiepoch frames for the sky around each exoplanet system to investigate reported companions and to identify new common proper-motion (CPM) companion candidates. We then confirmed or refuted many candidates through photometric distance estimates using plate magnitudes from SuperCOSMOS, optical CCD magnitudes from the Cerro Tololo Inter-American Observatory (CTIO) 0.9 and 1.0 m telescopes, and infrared magnitudes from the Two Micron All Sky Survey (2MASS). The origin and status of each companion are summarized in Table 2 and described in § 5.1.

Table 1 lists each target star in our sample, sequenced alphabetically by name, and identifies all known and new companions. Column (1) is the exoplanet host star's name (HD when available, otherwise BD or GJ name). Columns (2) and (3) give the proper-motion magnitude (in arcsec yr^{-1}) and direction (in deg) of the star, mostly from *Hipparcos*. Columns (4) and (5) specify the observational epochs of the DSS images blinked to identify CPM companion candidates. Column (6) lists the total proper motion (in arcsec) of the exoplanet host during the time interval between the two observational epochs of the DSS plates. Column (7) identifies whether the proper motion of the star was detectable in the DSS frames, allowing the identification of CPM candidates. The entries "Yes" and "No" are self-explanatory, and "Mar" identifies that the proper motion was marginally detectable. Systems with very little proper motion or a brief separation between plate epochs could not be searched effectively (see § 2.1). Column (8) specifies companions identified via CPM, and column (9) specifies companions listed in the sources mentioned above or in other refereed papers. A question mark following the companion ID indicates that the source remains a candidate and could not be confirmed or refuted with confidence. The absence of a question mark indicates that the companion is confirmed.

Each reference we used for the companion search is described in the subsections below.

2.1. *STScI Digitized Sky Survey*

We downloaded multiepoch images of the sky around each exoplanet primary from the STScI Digitized Sky Survey (DSS).[3] The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope in Australia. We typically extracted 10′ square images at two epochs centered on an exoplanet host star. The range of time interval between the epochs for a given target is 3.1–46.2 yr. Figure 1 shows a histogram of the number of systems per time interval bin for our sample.

We identified CPM companion candidates by eye, by blinking the two epoch frames. In general, primaries with a total proper motion of $\geq 3''$ were effectively searched, while those with a total proper motion in the range of $2''$–$3''$ were marginally searched, and stars with $\leq 2''$ total proper motion could not be searched for companions using this method. Exceptions to these ranges exist and are due to poorly matched astrometric fields caused by specific issues with the plate images, such as saturation around the primary, distribution of background stars in the frames, brightness of the companion and its proximity to the primary, and the relative rotation between the frames. The $3''$ detection limit corresponds to a proper-motion range of $0''.1$–$1''.0$ yr^{-1} with a median value of $0''.2$ yr^{-1} for the time intervals sampled. In addition, this method favors the detection of wide companions because bright primaries saturate the surrounding region out to many arcseconds and prevent companion detection within a $\sim 15''$–$30''$ radius, depending on source brightness. At the median distance

[1] See http://vo.obspm.fr/exoplanetes/encyclo/catalog.php.
[2] See http://exoplanets.org.
[3] See http://stdatu.stsci.edu/cgi-bin/dss_form.

TABLE 2

Exoplanet Systems with Stellar Companions

Sequence (1)	HD Name (2)	Other Name (3)	Component (4)	R.A. (J2000.0) (5)	Decl. (J2000.0) (6)	π (arcsec) (7)	Distance (pc) (8)	Basis (9)	Spectral Type (10)	Angular Separation (arcsec) (11)	P.A. (deg) (12)	Projected Separation (AU) (13)	$M \sin i$ (M_J) (14)	$a \sin i$ (AU) (15)	e (16)	Sources (17)	References (18)
1...............	000142	GJ 4.2	A	00 06 19.18	−49 04 30.7	0.03900	25.6	T	G1 IV	...	...	...	...	...	...	...	
	000142	...	b	...	...	...	...	...	...	...	...	...	1	0.98	0.38	...	
	000142	...	B	...	...	...	...	...	...	5.4	177	138	...	...	...	WC	1, 2
2...............	009826	υ And	A	01 36 47.84	+41 24 19.7	0.07425	13.5	T	F8.0 V	...	...	...	...	...	...	...	
	009826	...	b	...	...	...	...	...	...	...	...	...	0.69	0.059	0.012	...	
	009826	...	c	...	...	...	...	...	...	...	...	...	1.89	0.829	0.28	...	
	009826	...	d	...	...	...	...	...	...	...	...	...	3.75	2.53	0.27	...	
	009826	...	B	01 36 50.40	+41 23 32.1	...	...	...	M4.5 V	52	150	702	...	...	...	P	2, 3, 4
3...............	011964	GJ 81.1	A	01 57 09.61	−10 14 32.7	0.02943	34.0	T	G5	...	...	...	...	...	...	...	
	011964	...	b	...	...	...	...	...	...	...	...	...	0.11	0.229	0.15	...	
	011964	...	c	...	...	...	...	...	...	...	...	...	0.7	3.167	0.3	...	
	011964	...	B[a]	01 57 11.07	−10 14 53.2	...	...	...	...	29.7	133	1010	...	...	...	PWC	5, 6
4...............	013445	GJ 86	A	02 10 25.93	−50 49 25.4	0.09163	10.9	T	K1 V	...	...	...	...	...	...	...	
	013445	...	b	...	...	...	...	...	...	...	...	...	4.01	0.11	0.046	...	
	013445	...	B	...	...	...	...	...	WD	1.93	119	21	...	...	...	O	7, 8, 9
5...............	019994	GJ 128	A	03 12 46.44	−01 11 46.0	0.04469	22.4	T	F8.5 V	...	...	...	...	...	...	...	
	019994	...	b	...	...	...	...	...	...	...	...	...	2	1.3	0.2	...	
	019994	...	B	...	...	...	...	...	M	2.5	213	56	...	...	...	WCD	10, 11, 12, 13
6...............	027442	ϵ Ret	A	04 16 29.03	−59 18 07.8	0.05484	18.2	T	K2 IVa	...	...	...	...	...	...	...	
	027442	...	b	...	...	...	...	...	...	...	...	...	1.28	1.18	0.07	...	
	027442	...	B[a]	...	...	...	...	...	...	13.8	36	251	...	...	...	WCI	14, 15
7...............	038529	HIP 27253	A	05 46 34.91	+01 10 05.5	0.02357	42.4	T	G4 V	...	...	...	...	...	...	...	16
	038529	...	b	...	...	...	...	...	...	...	...	...	0.78	0.129	0.29	...	
	038529	...	c	...	...	...	...	...	...	...	...	...	12.7	3.68	0.36	...	
	038529	...	B[b]	05 46 19.38	+01 12 47.2	...	28.7	C	M3.0 V	284	305	12042	...	...	...	P	
8...............	041004	HIP 28393	A	05 59 49.65	−48 14 22.9	0.02324	43.0	T	K1 V	...	...	...	...	...	...	...	
	041004	...	b	...	...	...	...	...	...	...	...	...	2.3	1.31	0.39	...	
	041004	...	B	05 59 43.81	−48 12 11.9	...	...	...	M2.5 V	0.5	176	22	...	...	...	WH	4, 17, 18, 19
	041004	...	C	...	...	...	...	...	...	...	...	...	18.4	0.016	0.08	...	18, 19
9...............	040979	BD +44 1353	A	06 04 29.95	+44 15 37.6	0.03000	33.3	T	F8	...	...	...	...	...	...	...	
	040979		b	...	...	...	...	...	...	...	...	...	3.32	0.811	0.23	...	
	040979	BD +44 1351	B	06 04 13.02	+44 16 41.1	...	15.2	P	K5	192	290	6394	...	...	...	P	4, 16, 20, 21
10.............	046375	HIP 31246	A	06 33 12.62	+05 27 46.5	0.02993	33.4	T	K0 V	...	...	...	...	...	...	...	
	046375		b	...	...	...	...	...	...	...	...	...	0.249	0.041	0.04	...	
	046375		B[a]	06 33 12.10	+05 27 53.2	...	26.4	C	...	9.4	308	314	...	...	...	WI	22, 23
11.............	075289	HIP 43177	A	08 47 40.39	−41 44 12.5	0.03455	28.9	T	G0 V	...	...	...	...	...	...	...	
	075289	...	b	...	...	...	...	...	...	...	...	...	0.42	0.046	0.054	...	
	075289	...	B	08 47 42.26	−41 44 07.6	...	...	...	...	21.5	78	621	...	...	...	O	24
12.............	075732	55 Cnc	A	08 52 35.81	+28 19 50.9	0.07980	12.5	T	K0 IV–V	...	...	...	...	...	...	...	
	075732	...	e	...	...	...	...	...	...	...	...	...	0.045	0.038	0.174	...	
	075732	...	b	...	...	...	...	...	...	...	...	...	0.784	0.115	0.020	...	
	075732	...	c	...	...	...	...	...	...	...	...	...	0.217	0.24	0.44	...	
	075732	...	d	...	...	...	...	...	...	...	...	...	3.92	5.257	0.327	...	
	075732	...	B	08 52 40.85	+28 18 59.0	...	8.7	C	M4	84	130	1050	...	...	...	PWCD	4, 12, 25, 26, 27
13.............	080606	HIP 45982	A	09 22 37.57	+50 36 13.4	0.01713	58.4	T	G5	...	...	...	...	...	...	...	
	080606	...	b	...	...	...	...	...	...	...	...	...	3.41	0.439	0.927	...	
	080607	HIP 45983	B	09 22 39.73	+50 36 13.9	...	...	...	G5	20.6	269	1203	...	...	...	PWH	4, 28

TABLE 2—*Continued*

Sequence (1)	HD Name (2)	Other Name (3)	Component (4)	R.A. (J2000.0) (5)	Decl. (J2000.0) (6)	π (arcsec) (7)	Distance (pc) (8)	Basis (9)	Spectral Type (10)	Angular Separation (arcsec) (11)	P.A. (deg) (12)	Projected Separation (AU) (13)	$M \sin i$ (M_J) (14)	$a \sin i$ (AU) (15)	e (16)	Sources (17)	References (18)
14.............	089744	HIP 50786	A	10 22 10.56	+41 13 46.3	0.02565	39.0	T	F8 IV	…	…	…	…	…	…	…	
	089744	…	b	…	…	…	…	…	…	…	…	…	7.99	0.89	0.67	…	
	089744	…	B	10 22 14.87	+41 14 26.4	…	…	…	L0 V	63.0	48	2456	…	…	…	O	29, 30
15.............	099492	GJ 429B	B	11 26 46.28	+03 00 22.8	0.05559	18.0	T	K2 V	…	…	…	…	…	…	…	
	099492	…	b	…	…	…	…	…	…	…	…	…	0.122	0.119	0.05	…	
	099491	GJ 429A	A	11 26 45.32	+03 00 47.2	0.05659	17.7	T	K0 IV	28.6	150	515	…	…	…	PWHC	31
16.............	114729	HIP 64459	A	13 12 44.26	−31 52 24.1	0.02857	35.0	T	G3 V	…	…	…	…	…	…	…	
	114729	…	b	…	…	…	…	…	…	…	…	…	0.82	2.08	0.31	…	
	114729	…	B	13 12 43.97	−31 52 17.0	…	…	…	…	8.05	333	282	…	…	…	O	32
17.............	114762	HIP 64426	A	13 12 19.74	+17 31 01.6	0.02465	40.6	T	F9 V	…	…	…	…	…	…	…	
	114762	…	b	…	…	…	…	…	…	…	…	…	11.02	0.3	0.25	…	
	114762	…	B	…	…	…	…	…	…	3.26	30	132	…	…	…	O	3, 4
18.............	120136	τ Boo	A	13 47 15.74	+17 27 24.9	0.06412	15.6	T	F6 IV	…	…	…	…	…	…	…	
	120136	…	b	…	…	…	…	…	…	…	…	…	4.13	0.05	0.01	…	
	120136	…	B	…	…	…	…	…	…	2.87	31	45	…	…	…	WCD	3, 4, 12
19.............	142022	GJ 606.1	A	16 10 15.02	−84 13 53.8	0.02788	38.9	T	G8/K0 V	…	…	…	…	…	…	…	
	142022	…	b	…	…	…	…	…	…	…	…	…	4.4	2.8	0.57	…	
	142022	…	B	16 10 25.34	−84 14 06.7	…	…	…	K7 V	20.4	130	794	…	…	…	PWC	33, 34
20.............	147513	GJ 620.1	A	16 24 01.29	−39 11 34.7	0.07769	12.9	T	G5 V	…	…	…	…	…	…	…	
	147513	…	b	…	…	…	…	…	…	…	…	…	1	1.26	0.52	…	
	147513	…	B	16 23 33.83	−39 13 46.1	0.07804	12.8	T	WD	345	245	4451	…	…	…	C	13, 35
21.............	178911B	HIP 94076B	B	19 09 03.10	+34 35 59.5	0.02140	46.7	T	G5	…	…	…	…	…	…	…	
	178911B	…	b	…	…	…	…	…	…	…	…	…	6.292	0.32	0.124	…	
	178911	HIP 94076	A	19 09 04.38	+34 36 01.6	0.02042	49.0	T	G1 V J	16.1	82	789	…	…	…	PWH	4, 36, 37, 38, 39
	178911	…	C[c]	…	…	…	…	…	…	0.1	21	4.9	…	…	…	W	
22.............	186427	16 Cyg B	B	19 41 51.97	+50 31 03.1	0.04670	…	…	G3 V	…	…	…	…	…	…	…	
	186427	…	b	…	…	…	…	…	…	…	…	…	1.69	1.67	0.67	…	
	186408	16 Cyg A	A	19 41 48.95	+50 31 30.2	0.04625	21.6	T	G1.5 V J	39.8	313	860	…	…	…	PWC	2, 3, 4, 40, 41
	186408	…	C[c]	…	…	…	…	…	…	3.4	209	73	…	…	…	W	
23.............	188015	HIP 97769	A	19 52 04.54	+28 06 01.4	0.01900	52.6	T	G5 IV	…	…	…	…	…	…	…	
	188015	…	b	…	…	…	…	…	…	…	…	…	1.26	1.19	0.15	…	
	188015	…	B[b]	19 52 05.51	+28 06 03.7	…	46.9	C	…	13	85	684	…	…	…	P	
24.............	190360	GJ 777	A	20 03 37.41	+29 53 48.5	0.06292	15.9	T	G7 IV–V	…	…	…	…	…	…	…	
	190360	…	c	…	…	…	…	…	…	…	…	…	0.057	0.128	0.01	…	
	190360	…	b	…	…	…	…	…	…	…	…	…	1.502	3.92	0.36	…	
	190360	…	B	20 03 26.58	+29 51 59.5	…	18.5	P	M4.5 V	179	234	2846	…	…	…	PWC	4, 5, 16, 42
25.............	195019	HIP 100970	A	20 28 18.64	+18 46 10.2	0.02677	37.3	T	G3 IV–V	…	…	…	…	…	…	…	
	195019	…	b	…	…	…	…	…	…	…	…	…	3.43	0.14	0.05	…	
	195019	…	B	…	…	…	…	…	…	3.5	330	131	…	…	…	W	4, 5, 43, 44
26.............	196050	HIP 101806	A	20 37 51.71	−60 38 04.1	0.02131	46.9	T	G3 V	…	…	…	…	…	…	…	
	196050	…	b	…	…	…	…	…	…	…	…	…	3	2.5	0.28	…	
	196050	…	B	20 37 51.85	−60 38 14.9	…	…	…	…	10.9	175	510	…	…	…	O	32
27.............	213240	HIP 111143	A	22 31 00.37	−49 25 59.8	0.02454	40.8	T	G0/G1 V	…	…	…	…	…	…	…	
	213240	…	b	…	…	…	…	…	…	…	…	…	4.5	2.03	0.45	…	
	213240	…	B	22 31 08.26	−49 26 56.7	…	41.8	C	M5.0 V	95.8	127	3909	…	…	…	P	32

TABLE 2—*Continued*

Sequence (1)	HD Name (2)	Other Name (3)	Component (4)	R.A. (J2000.0) (5)	Decl. (J2000.0) (6)	π (arcsec) (7)	Distance (pc) (8)	Basis (9)	Spectral Type (10)	Angular Separation (arcsec) (11)	P.A. (deg) (12)	Projected Separation (AU) (13)	$M \sin i$ (M_J) (14)	$a \sin i$ (AU) (15)	e (16)	Sources (17)	References (18)
28.............	219449	GJ 893.2	A	23 15 53.49	−09 05 15.9	0.02197	45.5	T	K0 III	...	...	...	...	...	...	...	
	219449	...	b	...	...	...	...	...	...	...	...	...	2.9	0.3	–	...	
	219430	...	B[a]	23 15 51.00	−09 04 42.7	...	42.4[d]	C	K8 V J	49.4	313	2248	...	...	...	PWC	6, 45
	219430	...	C[a,e]	...	...	...	42.4[d]	C	...	0.4	101	18	...	...	...	W	
29.............	222404	γ Cephei	A	23 39 20.85	+77 37 56.2	0.07250	13.8	T	K1 III	...	...	...	...	...	...	...	
	222404	...	b	...	...	...	...	...	...	...	...	...	1.59	2.03	0.2	...	
	222404	...	B	...	...	...	...	...	...	...	...	...	...	20.3	0.39	H	4, 46, 47, 48, 49
30.............	222582	HIP 116906	A	23 41 51.53	−05 59 08.7	0.02384	42.0	T	G5	...	...	...	...	...	...	...	
	222582	...	b	...	...	...	...	...	...	...	...	...	5.11	1.35	0.76	...	
	222582	...	B[a]	23 41 45.14	−05 58 14.8	...	32.1	C	M3.5 V	113	302	4746	...	...	...	PW	6
Candidate (Unconfirmed) Stellar Companions																	
31.............	008673	HIP 6702	A	01 26 08.78	+34 34 46.9	0.02614	38.3	T	F7 V	...	...	...	...	...	...	...	
	008673	...	b	...	...	...	...	...	...	...	...	...	14	1.58	–	...	
	008673	...	B	...	...	...	...	...	...	0.1	78	3.8	...	...	...	W	
32.............	016141	HIP 12048	A	02 35 19.93	−03 33 38.2	0.02785	35.9	T	G5 IV	...	...	...	...	...	...	...	
	016141	...	b	...	...	...	...	...	...	...	...	...	0.23	0.35	0.21	...	
	016141	...	B	02 35 19.88	−03 33 43.9	...	...	...	...	6.2	188	222	...	...	...	O	32
33.............	111232	HIP 62534	A	12 48 51.75	−68 25 30.5	0.03463	28.9	T	G8 V	...	...	...	...	...	...	...	
	111232	...	b	...	...	...	...	...	...	...	...	...	6.8	1.97	0.2	...	
	111232	...	B	...	...	...	...	...	...	...	...	...	...	...	...	H	13
34.............	150706	GJ 632	A	16 31 17.59	+79 47 23.2	0.03673	27.2	T	G0	...	...	...	...	...	...	...	
	150706	...	b	...	...	...	...	...	...	...	...	...	1	0.82	0.38	...	
	150706	...	B	...	...	...	...	...	...	...	...	...	...	...	...	H	50
35.............	169830	HIP 90485	A	18 27 49.48	−29 49 00.7	0.02753	36.3	T	F9 V	...	...	...	...	...	...	...	
	169830	...	b	...	...	...	...	...	...	...	...	...	2.88	0.81	0.31	...	
	169830	...	c	...	...	...	...	...	...	...	...	...	4.04	3.6	0.33	...	
	169830	...	B[f]	18 27 48.65	−29 49 01.6	...	...	...	...	11	270	399	...	...	...	...	
36.............	217107	HIP 113421	A	22 58 15.54	−02 23 43.4	0.05071	19.7	T	G8 IV–V	...	...	...	...	...	...	...	
	217107	...	b	...	...	...	...	...	...	...	...	...	1.37	0.074	0.13	...	
	217107	...	c	...	...	...	...	...	...	...	...	...	2.1	4.3	0.55	...	
	217107	...	B	...	...	...	...	...	...	0.3	156	6	...	...	...	W	51, 52

Notes.—Planet data are from the Exoplanet Encyclopedia Web site, http://vo.obspm.fr/exoplanetes/encyclo/catalog.php. Table 2 is also available in machine-readable form in the electronic edition of the *Astrophysical Journal*.

[a] Known companion, but first identification of the star as a companion to an exoplanet host.

[b] New stellar companion reported by this work.

[c] Separation and position angle are listed with respect to component A. A and C have been referred to as Aa and Ab, respectively, in other publications, but we follow a consistent naming convention, using uppercase letters to represent stars and lowercase letters to denote planets.

[d] Photometry obtained is for the BC pair. Distance estimate assumes identical binary components.

[e] Separation and position angle are listed with respect to component B.

[f] New candidate companion reported by this work, via Kevin Apps.

References.—(1) Bailey 1900; (2) Lowrance et al. 2002; (3) Patience et al. 2002; (4) Eggenberger et al. 2004; (5) Allen et al. 2000; (6) Zacharias et al. 2004; (7) Els et al. 2001; (8) Mugrauer & Neuhäuser 2005; (9) Queloz et al. 2000; (10) Smyth 1844; (11) Hale 1994; (12) Duquennoy & Mayor 1991; (13) Mayor et al. 2004; (14) Jessup 1955; (15) Holden 1966; (16) Lepine & Shara 2005; (17) See 1897; (18) Zucker et al. 2003; (19) Zucker et al. 2004; (20) Hog et al. 1998; (21) Halbwachs 1986; (22) Soulie 1985; (23) Urban et al. 1998; (24) Mugrauer et al. 2004a; (25) van Altena et al. 1995; (26) Dahn et al. 1988; (27) Marcy et al. 2002; (28) Naef et al. 2001; (29) Wilson et al. 2001; (30) Mugrauer et al. 2004b; (31) Marcy et al. 2005b; (32) Mugrauer et al. 2005; (33) Luyten 1979; (34) Eggenberger et al. 2006; (35) Wegner 1973; (36) McAlister et al. 1987b; (37) Balega et al. 2004; (38) Hartkopf et al. 2000; (39) Zucker et al. 2002; (40) Turner et al. 2001; (41) Cochran et al. 1997; (42) Naef et al. 2003; (43) Hough 1887; (44) Fischer et al. 1999; (45) Wilson 1953; (46) Mason et al. 2001; (47) Campbell et al. 1988; (48) Griffin et al. 2002; (49) Hatzes et al. 2003; (50) Halbwachs et al. 2003; (51) McAlister et al. 1987a; (52) Mason et al. 1999.

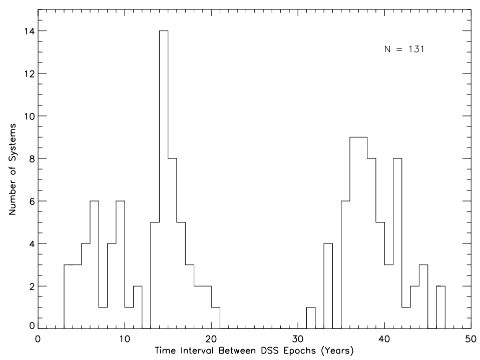

Fig. 1.—Histogram of time intervals between DSS epochs for the exoplanet sample.

of 35.6 pc for our sample, this translates to a minimum projected distance of ~500–1000 AU. However, some bright companions can be picked up much closer, due to twin diffraction spikes or an anomalous point-spread function (PSF) compared to other stars in the field. For an outer limit, the 10′ image gives us a radius of 5′, which translates to a projected distance of ~10,000 AU for the median distance of the exoplanet sample. This is of the order of magnitude of the canonical limit for gravitational binding, although Poveda et al. (1994) listed several companions with separations larger than this.

Of the 131 systems, 82 had easily detectable proper motions and hence were searched effectively for CPM companions, 7 had marginal proper motions, and 42 systems had no detectable proper motions. Of the 82 systems searched effectively, 15 definite CPM companions were confirmed (one per system), and 67 had no CPM companions detected within the search region outlined above. However, in 12 (plus 3 candidates) of these 67 systems, close companions were identified by other sources. In 3 (plus 3 candidates) of the 49 marginal or unsearched systems, companions were reported by other sources. These additional companions could not be detected by our method due to saturation around the primary and/or a short time baseline between the DSS image pair.

2.2. *Washington Double Star Catalog* (*WDS*)

The WDS catalog[4] is the world's most comprehensive database of multiple stars. However, it is a catalog of doubles, not binaries, so it explicitly contains an unknown number of nonphysical chance alignments. Table 3 lists 20 WDS entries that are not gravitationally bound to the exoplanet host, but rather are field stars, listed in WDS ID sequence (col. [1]). Column (2) is the HD identifier of the star. Column (3) is the component suffix

[4] See http://ad.usno.navy.mil/wds.

TABLE 3
WDS Entries that Are Not Gravitationally Bound Companions

WDS ID (1)	HD Name (2)	Component (3)	θ (deg) (4)	ρ (arcsec) (5)	Epoch (6)	Number (7)	Notes (8)
00394+2115	003651	...	80	167.6	1997	9	1
01368+4124	009826	AB	128	114.0	1909	1	1
01368+4124	009826	AC	289	273.6	1991	7	1
03329−0927	022049	...	143	0.0	1975	1	2
11268+0301	099492	AC	187	90.5	1937	3	1
13284+1347	117176	AB	127	268.6	2002	13	1
13284+1347	117176	AC	263	325.5	1923	1	1
13573−5602	121504	...	55	36.2	1999	32	3
15249+5858	137759	...	50	254.8	2002	12	4
16010+3318	143761	...	49	135.3	2002	22	1
19091+3436	178911	Aa-C	130	60.0	1944	1	1
20140−0052	192263	A-BC	102	73.1	2003	19	1
20140−0052	192263	AD	244	71.3	1921	1	1
20140−0052	192263	BC-D	65	23.5	1998	8	1
20283+1846	195019	AC	72	70.9	1998	11	1
20283+1846	195019	AD	97	84.5	1998	2	1
20399+1115	196885	...	6	182.9	2000	13	1
22310−4926	213240	...	359	21.9	1999	7	1
23159−0905	219449	AD	274	80.4	1924	6	1
23159−0905	219449	BC-E	341	19.7	1924	6	1

Notes.—Cols. (1), (3), and (7) are listed here exactly as in the WDS catalog. Cols. (4), (5), and (6) correspond to the most recent observation. All data are as of 2005 June 20. Certain pairs of multiple systems omitted from this table are confirmed to be gravitationally bound companions (01368+4124AD, 11268+0301AB, 19091+3436Aa and Aa-B, 20283+1846AB, and 23159−0905A-BC and BC). One omitted pair (20140−0052BC) has several speckle observations (Jonckheere 1911, 1917, 1944; Vanderdonck 1911; Van Biesbroeck 1960) and several failed attempts (van den Bos 1949, 1960, 1963; Couteau 1954; Baize 1957) and is hence inconclusive. Col. (8) notes: (1) DSS multiepoch plates do not show CPM for WDS entry. In fact, proper motion of the primary star causes change in separation and position angle, indicating that the "companion" is a background star. (2) Primary star is ϵ Eri, the well-studied exoplanet system. WDS listing is based on a single speckle measure by Blazit et al. (1977). This system has been observed 13 other times and no companion was resolved (McAlister 1978; Hartkopf & McAlister 1984; Oppenheimer et al. 2001). (3) Primary's $\mu = 0.''264$ yr^{-1} at 251° from *Hipparcos* is not detectable in DSS plates. For the WDS companion, SuperCOSMOS lists $\mu = 0.''013$ yr^{-1} at 91°, clearly not matching the primary's. (4) Primary does not show detectable proper motion in DSS plates. Planet discovery paper, Frink et al. (2002), refuted the WDS entry based on distance estimate to WDS entry and proper-motion comparisons.

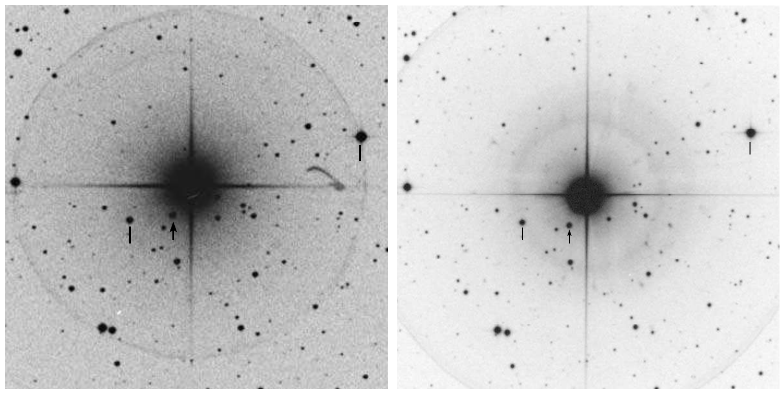

Fig. 2.—DSS images from two epochs for HD 9826. The 10′ square images have north up and east to the left. WDS lists components B and C (marked by lines), which are background stars. WDS component D (marked by an arrow), however, is a CPM companion. The primary's $\mu = 0\farcs42\ \mathrm{yr}^{-1}$ at 204°.

of the pair, as it appears in the WDS catalog, for which position angle, separation, and epoch of the most recent observation are listed in columns (4), (5), and (6). Column (7) is the number of observations listed in the WDS. Note that a few of these "companions" have many observations, but they are not true companions. Column (8) identifies the specific method used to refute the WDS entry.

Figure 2 shows an example for HD 9826. The lines mark two WDS entries that do not share the primary's high proper motion and hence are background stars. On the other hand, the known CPM companion (marked by an arrow) is easily identifiable in these images.

2.3. *Hipparcos Catalog*

As most of the exoplanet systems are close to the Sun (128 of the 131 are within 100 pc), the *Hipparcos* Catalog[5] provides fairly reliable distances and some photometric data for these systems. The catalog also notes some stellar companions, identified by field H59 as component solutions ("C" flag), accelerated proper motions ("G" flag), or orbital solutions ("O" flag). In total, *Hipparcos* identified stellar companions in nine exoplanet systems, four each with C and G flags, and one with the O flag. Five of the nine *Hipparcos* companions were independently confirmed, one (HD 38529c) is a close brown dwarf, and two (both G flags) remain as candidates. The ρ CrB system (HD 143761) has an O flag and contains a companion that is a planet (Noyes et al. 1997; Zucker & Mazeh 2001) or a star (Gatewood et al. 2001; Pourbaix & Arenou 2001; Halbwachs et al. 2003), but not both.

2.4. *Catalog of Nearby Stars*

Among our sample of 131 stars, 39 are listed in the CNS. We reviewed the earlier versions of the catalog (Gliese 1969; Gliese & Jahreiss 1979, 1991), as well as the consolidated information on the Web.[6] The catalog identifies any known companions and lists separation, position angle, and references in the notes section. Twelve stars from our sample have companions listed in the CNS, and every one of them was confirmed by other sources to be a true companion.

2.5. *Duquennoy & Mayor*

The Duquennoy & Mayor (1991) G Dwarf Survey specifically looked at multiplicity among solar-type stars in the solar neighborhood using radial velocity techniques. This is an ideal reference for our sample because searches for exoplanet systems have focused on such systems. Duquennoy & Mayor (1991) identified target stars as single-line, double-line, or line width spectroscopic binaries, or spectroscopic binaries with orbits. Only three stars from our sample have companions listed in this reference, and each of these was confirmed by other sources to be a true companion.

3. PHOTOMETRIC DISTANCE ESTIMATES FOR COMPANION CANDIDATES

In addition to the proper-motion investigation, we collected archival 2MASS and SuperCOSMOS photometry and new CCD photometry that allowed us to compute distance estimates to companion candidates, as described below. Table 4 summarizes the photometry data, as well as the distance estimates computed. Column (1) is the star's name, and column (2) contains the spectral type identified as part of this work (see § 4). Columns (3), (4), and (5) are the *BRI* plate magnitudes from SuperCOSMOS, followed by the *VRI* CCD magnitudes observed by us at the CTIO 0.9 and 1.0 m telescopes in columns (6), (7), and (8). Column (9) gives the number of observations available for the *VRI* photometry. This is followed by 2MASS JHK_s photometry in columns (10), (11), and (12). Columns (13), (14), and (15) are the estimated plate photometric distance, total error of this estimate, and the number of color relations used in computing this estimate. Columns (16), (17), and (18) similarly list the CCD distance estimate, total error, and the number of color relations used.

3.1. *2MASS Coordinates and Photometry*

We used the 2MASS Web database, accessed via the Aladin interactive sky atlas[7] (Bonnarel et al. 2000), to obtain equinox

[5] See http://www.rssd.esa.int/Hipparcos/HIPcatalogueSearch.html.
[6] See http://www.ari.uni-heidelberg.de/aricns.
[7] See http://aladin.u-strasbg.fr/aladin.gml.

TABLE 4

OBSERVATIONS AND COMPUTED DISTANCES

Name (1)	Spectral Type (2)	Plate Magnitudes B (3)	Plate Magnitudes R (4)	Plate Magnitudes I (5)	CCD Magnitudes V (6)	CCD Magnitudes R (7)	CCD Magnitudes I (8)	Number of Observations (9)	Infrared Magnitudes J (10)	Infrared Magnitudes H (11)	Infrared Magnitudes K_s (12)	D_{plt} (pc) (13)	Error (pc) (14)	Number of Relations (15)	D_{CCD} (pc) (16)	Error (pc) (17)	Number of Relations (18)
Exoplanet Host Without Parallax																	
BD −10 3166	...	9.90	8.80	8.08	10.03	9.59	9.19	1	8.61	8.30	8.12	33.8	8.8	1	66.8	10.0	1
Confirmed Companions																	
HD 038529B	M3.0 V	13.81	11.84	10.05	13.35	12.29	10.98	3	9.72	9.04	8.80	31.8	9.0	11	28.7	4.8	12
HD 040979B	...	9.92	8.72	...	...	...	...	...	7.27	6.79	6.69	15.2	4.0	3	...	...	...
HD 046375B	...	...	...	...	11.80	11.01	9.80	3	8.70	8.08	7.84	...	...	...	26.4	6.0	12
HD 075732B	...	13.14	11.53	...	13.26	11.91	10.24	2	8.56	7.93	7.67	14.5	4.6	6	8.7	1.4	12
HD 188015B	...	...	...	...	...	15.54	13.91	1	12.09	11.59	11.34	...	...	...	46.9	9.5	7
HD 190360B	...	15.30	12.35	...	...	...	...	...	9.55	9.03	8.71	18.5	6.2	6	...	...	...
HD 213240B	M5.0 V	...	...	...	17.40	15.96	14.13	1	12.36	11.74	11.47	...	...	...	41.8	6.5	12
HD 219449BC	Early K	...	...	...	9.17	8.57	8.05	1	7.31	6.84	6.69	...	...	...	29.9	4.7	6
HD 222582B	M3.5 V	15.25	13.16	11.41	14.49	13.33	11.83	1	10.39	9.81	9.58	35.1	9.3	11	32.1	5.0	12
Candidate Companions																	
HD 169830B	...	...	...	...	14.35	13.62	12.39	1	10.16	9.50	9.35	...	...	...	29.2	23.4	12
Refuted Candidate Companions																	
BD −10 3166 #1	M5.0 V	14.71	13.36	11.78	14.43	13.03	11.22	1	9.51	8.97	8.64	16.4	10.1	11	12.5	2.0	12
HD 033636 #1	M1.0 V	20.56	18.17	...	19.31	18.43	17.37	1	16.26	15.63	15.16	608.5	162.9	6	738.9	162.3	12
HD 041004 #1	M0.5 V–VI	18.90	16.87	15.76	17.89	16.91	16.05	1	15.06	14.50	14.16	414.0	119.1	11	557.4	103.3	9
HD 072659 #1	M3.0 V	20.21	18.05	16.43	18.91	18.02	16.53	1	15.31	14.67	14.30	293.0	82.5	11	368.6	99.2	12
HD 114783 #1	Early K	10.60	9.32	8.92	9.78	9.31	8.90	2	8.32	7.90	7.79	20.2	5.4	3	54.0	9.3	2

J2000.0 coordinates for the companion candidates, the epoch of observation, and *J*, *H*, and K_s photometry. The errors in JHK_s were almost always less than 0.05 mag and were typically 0.02–0.03 mag. Notable exceptions are three distant and faint refuted candidates listed in Table 4, HD 33636 #1 (errors of 0.14, 0.15, null at JHK_s, respectively), HD 41004 #1 (0.05, 0.06, and 0.07 mag), and HD 72659 #1 (0.05, 0.06, and 0.07 mag).

3.2. *SuperCOSMOS Plate Photometry and Distance Estimates*

We obtained optical plate photometry in B_J, R_{59F}, and I_{IVN} bands (hereafter *BRI*) from the SuperCOSMOS Sky Survey (SSS) scans of Schmidt survey plates (Hambly et al. 2001b). The SSS plate photometry is calibrated by means of a network of secondary standard-star sequences across the entire sky, with the calibration being propagated into fields without standards by means of the ample overlap regions between adjacent survey fields. The external accuracy of the calibrations is ±0.3 mag in individual passbands (Hambly et al. 2001a); however, the internal accuracy in colors (e.g., $B - R$, $R - I$) is much better, being typically 0.1 mag for well-exposed, uncrowded images. We used point-source photometric measures in all cases.

Photometric distance estimates were then derived using these SSS plate magnitudes, combined with 2MASS JHK_s by fitting various colors to M_{K_s}-color relations from Hambly et al. (2004). Results for 11 companion candidates are given in Table 4. Errors quoted from this procedure include internal and external errors. Internal errors represent the standard deviation of distance estimates from the suite of M_{K_s}-color relations. External errors represent a measure of the reliability of the relations for stars of known distance, which is estimated to be 26% in Hambly et al. (2004).

3.3. *CCD Photometry Observations and Distance Estimates*

Because of the relatively large photometric distance errors associated with photographic plate photometry, we obtained optical CCD photometry for one exoplanet host and 13 companion candidates (given in Table 4) in the $V_J R_{KC} I_{KC}$ bands (hereafter *VRI*) using the CTIO 0.9 and 1.0 m telescopes during observing runs in 2003 December, 2004 June, September, and December, 2005 August and December, and 2006 March as part of the SMARTS (Small and Moderate Aperture Research Telescope System) Consortium. For the 0.9 m telescope, the central quarter of the 2048 × 2046 Tektronix CCD camera was used with the Tek 2 *VRI* filter set. For the 1.0 m telescope, the Y4KCam CCD camera was used with the Harris 1 4mts *VR* and kc 1 4mts *I* filter set. Standard stars from Graham (1982), Bessel (1990), and Landolt (1992) were observed through a range of air masses each night to place measured fluxes on the Johnson-Kron-Cousins *VRI* system and to calculate extinction corrections.

Data were reduced using IRAF via typical bias subtraction and dome flat-fielding, using calibration frames taken at the beginning of each night. In general, a circular aperture 14″ in diameter was used to determine stellar fluxes in order to match apertures used by Landolt (1992) for the standard stars. In cases of crowded fields, an appropriate aperture 2″–12″ in diameter was used to eliminate stray light from close sources and aperture corrections were applied. For one target (HD 169830B), we used Gaussian fitting via an IDL program to the PSF tail of a bright nearby source to eliminate its effects and completed the photometry on the target using the IDL APER routine. The same approach was performed on two of our standard stars to correct for zero-point difference between IDL and IRAF magnitudes. As discussed in Henry et al. (2004), photometric errors are typically ±0.03 mag or less, which includes both internal and external errors. The only exceptions with larger errors were distant and faint refuted candidates HD 33636 #1 (errors of 0.06, 0.04, and 0.04 mag at *V*, *R*, and *I*, respectively) and HD 72659 #1 (0.10, 0.05, and 0.03 mag), new companion HD 188015B (0.05 and 0.04 mag at *R* and *I*, respectively), and new candidate HD 169830B (0.12, 0.09, and 0.13 mag). The errors for HD 188015B and HD 169830B are high due to the uncertainties introduced by the large-aperture corrections and, for HD 169830B, PSF fitting as well.

Photometric distances were obtained using the *VRI* magnitudes along with 2MASS JHK_s and fitting various colors to M_{K_s}-color relations from Henry et al. (2004). The results for these companion candidates are given in columns (16)–(18) of Table 4. Errors quoted from this procedure include internal and external errors. Internal errors represent the standard deviation of distance estimates from the suite of M_{K_s}-color relations. External errors represent a measure of the reliability of the relations for stars of known distance, which is estimated to be 15% in Henry et al. (2004).

4. SPECTROSCOPIC OBSERVATIONS

New spectra of nine companion candidates were obtained during observing runs in 2003 October and December, 2004 March and September, and 2005 January at the CTIO 1.5 m telescope as part of the SMARTS Consortium. The Ritchey-Chrétien spectrograph and Loral 1200 × 800 CCD detector were used with grating 32 in our red setup and grating 09 in our blue setup, which provided 8.6 Å resolution and wavelength coverage over 6000–9500 Å in the red and 3800–6800 Å in the blue. Data reduction consisted of background subtraction, spectrum extraction, and wavelength and flux calibrations in IRAF after standard bias subtraction, flat-fielding, and illumination corrections were applied. Standard dome flats were used for flat-fielding and calibration frames were taken at the beginning of each night. Fringing at wavelengths longer than 7000 Å is common in data from this spectrograph; however, it is typically removed fully by flat-fielding, and no further steps were needed to remove the fringes. Spectral types for stars observed in the red wavelength regime, listed in Table 4, were assigned using the ALLSTAR program as described in Henry et al. (2002). RECONS types have been assigned using a set of standard comparison stars from the RECONS database, a library of ∼500 M0.0 V–M9.0 V spectra. Only rough spectral types were assigned based on our blue spectra by comparing features in our spectra with standard stars in Jacoby et al. (1984).

5. RESULTS

Table 2 is a compendium of the 30 exoplanet systems confirmed to have two or more stellar components, listed in coordinate sequence. At the end of the table, six additional systems are listed that may be stellar multiples, although these have not yet been confirmed. Column (1) lists a sequence number of the exoplanet system matching the value plotted in Figure 5, and columns (2) and (3) list the HD name and an alternate name of the exoplanet host and companion stars. Column (4) lists stellar (A, B, C, . . .) or planetary components (b, c, d, . . .). Columns (5) and (6) list the right ascension and declination of stars at epoch 2000.0, equinox J2000.0. For stars listed in *Hipparcos* (all primaries and a few companions), we used the *Hipparcos* 1991.25 epoch coordinates and proper motions to compute the coordinates listed. For fainter stars not observed by *Hipparcos*, we used 2MASS coordinates at the epoch of observation and converted the coordinates to epoch 2000.0 using proper motions from SuperCOSMOS or NLTT (Luyten 1979),[8] if available.

[8] Also available via the VizieR Online Data Catalog I/98A.

When the proper motion of a companion was not available, we used the primary's *Hipparcos* proper motion. In some instances, 2MASS coordinates were not available for the companions, and in these instances, the coordinates of the companions are not listed. However, in all but three of these cases, the separation and position angle of the companion from the primary are listed in columns (11) and (12). The three exceptional cases (one confirmed and two candidates), where neither coordinates nor separations from the primaries are known, are all *Hipparcos* G flags and hence close astrometric binaries. Column (7) lists the trigonometric parallax from *Hipparcos*, in arcseconds. Columns (8) and (9) list the distance, in pc, and its basis on either trigonometric parallax, if available (coded as "T"), calculated CCD photometric distance using relations from Henry et al. (2004) (coded as "C"), or calculated plate magnitude distance from SuperCOSMOS using relations from Hambly et al. (2004) (coded as "P"). If both plate and CCD distance estimates are available, only the more reliable CCD distance is listed. Column (10) lists the spectral type from Gray et al. (2003), the planet discovery paper, or other references for the primary and from our spectroscopic observations or other references for the companion. Columns (11) and (12) list the angular separation (in arcsec) and position angle (in deg) of stellar companions with respect to the exoplanet host. For companions listed in WDS, these are typically the most recent entry in WDS; otherwise, they are the values listed in the companion discovery paper. For new companions, these astrometry values are our measurements from our CTIO or the DSS images. Column (13) lists the projected spatial separation (and is therefore a lower limit at the epoch of plate observation) of companion stars with respect to their primaries, in AU. Column (14) gives the $M \sin i$ in Jupiter masses for planets. Columns (15) and (16) list the $a \sin i$ (in AU) and eccentricity of the orbits. Column (17) specifies the sources used to detect the companion stars. The codes are as follows: "P" represents a CPM detection using the multiepoch DSS images; "W" represents a companion listing in the WDS catalog; "H" represents a *Hipparcos* catalog companion identification; "C" represents a companion identification in the CNS catalog; "D" represents a companion identification in Duquennoy & Mayor (1991); "I" represents confirmation via our recent *VRI* images taken to verify CPM; and "O" represents that the companion was not found by any of the above means but reported in one or more refereed papers. Finally, column (18) lists relevant references relating to stellar companions. We have chosen not to list the individual planet discovery papers as references, unless they identify a stellar companion.

5.1. *Notes for Each Multiple System*

5.1.1. *New, Known, or Confirmed Companion Systems*

HD 142.—This close binary (separation $5''.4$) is listed in WDS and CNS. While this pair was first resolved at Harvard College Observatory in 1894 (Bailey 1900), the separation and $\Delta m \simeq 5$ make this a difficult object. It was found at approximately the same position six times from 1894 to 1928. It then remained unmeasured for 72 yr until it became evident in 2MASS in 2000 at approximately the same position angle. Given the primary's $\mu = 0''.58$ yr^{-1} due east and the long time lapse between the 1928 WDS observation and our image of 2004, a background star would easily have been detected, but we found a blank field at its expected position. This system was mentioned in Lowrance et al. (2002) as a single planet in a multiple-star system.

HD 9826.—This CPM pair is clearly identified in DSS images but not listed in any of the other sources checked. Lowrance et al. (2002) identified this as the first system discovered with multiple planets and multiple stars. It was also mentioned in Patience et al. (2002) and Eggenberger et al. (2004) as an exoplanet primary having a stellar companion.

HD 11964.—This CPM pair is clearly identified in DSS images and listed in WDS and CNS. Allen et al. (2000) listed this as a wide binary system in a catalog of 122 binaries identified via CPM from a sample of 1200 high-velocity, metal-poor stars. The primary's $\mu = 0''.441$ yr^{-1} at 237° from *Hipparcos*, and the companion's $\mu = 0''.444$ yr^{-1} at 236° (Zacharias et al. 2004), a good match. Our work is the first identification of this as a stellar companion to a planetary system.

HD 13445.—Els et al. (2001) reported the discovery of this close companion ($1''.72 \pm 0''.2$ separation) via AO imaging, incorrectly identifying the companion as a T dwarf based on its colors. The recent publication of Mugrauer & Neuhäuser (2005) identified this companion as a cool white dwarf based on its spectrum, claiming the first white dwarf discovery in a planetary system. However, HD 147513 was in fact the first white dwarf discovery in a planetary system, reported by Mayor et al. (2004). There are now two known systems with evidence of planets surviving the post–main-sequence evolution of a stellar companion, with this one being the closest known white dwarf companion to an exoplanet host (at a projected separation of just 21 AU, similar to the Sun–Uranus distance).

HD 19994.—WDS lists 14 observations for this companion. This pair was first resolved by Admiral Smyth in 1836 with a 6 inch refractor (Smyth 1844). It has been resolved 15 times since then, most recently by Hale (1994), who also calculated a 1420 yr orbit for this pair. While there is some hint of curvilinear motion in the data, the orbit is certainly preliminary. This companion is also listed in CNS and Duquennoy & Mayor (1991). Several references have identified this as a stellar companion to a planetary system (Lowrance et al. 2002; Mayor et al. 2004; Eggenberger et al. 2004; Udry et al. 2004).

HD 27442.—WDS and CNS list this companion at $13''.8$ separation at 36°. It was first resolved in 1930 by Jessup (1955) and measured again by Holden (1966) almost 35 years later at approximately the same position. Our short-exposure *VRI* images taken at CTIO in 2004 September identified a source about $13''$ away at 34°, consistent with the observations of almost 75 years ago. Given the primary's $\mu = 0''.175$ yr^{-1}, this can be confirmed as a companion. Our work is the first identification of this as a stellar companion to a planetary system.

HD 38529.—This CPM pair was discovered by us using DSS images. The primary's $\mu = 0''.163$ yr^{-1} at 209° from *Hipparcos*, and the companion's $\mu = 0''.162$ yr^{-1} at 204° from Lepine & Shara (2005)[9] and $0''.158$ yr^{-1} at 208° from SuperCOSMOS. Figure 3 includes two DSS images showing the primary and the companion. Our CCD photometric distance estimate of 28.7 ± 4.8 pc is consistent with our spectral identification of M3.0 V and matches the primary's distance of 42 pc within 3 σ. At our request, spectroscopic observations of the companion were obtained by G. Fritz Benedict in 2004 February using the McDonald Observatory 2.1 m telescope and Sandiford Cassegrain echelle spectrograph (McCarthy et al. 1993). The data were reduced and one-dimensional spectra were extracted using the standard IRAF `echelle` package tools. The radial velocity was determined by cross-correlating the spectra of the star with that of an M2 dwarf (GJ 623) template using the IRAF task `fxcor`. The adopted radial velocity for the GJ 623 primary (it is a binary) was -29.2 km s^{-1}, given the orbital phase at which the template was secured and a

[9] Also available via the VizieR Online Data Catalog I/298.

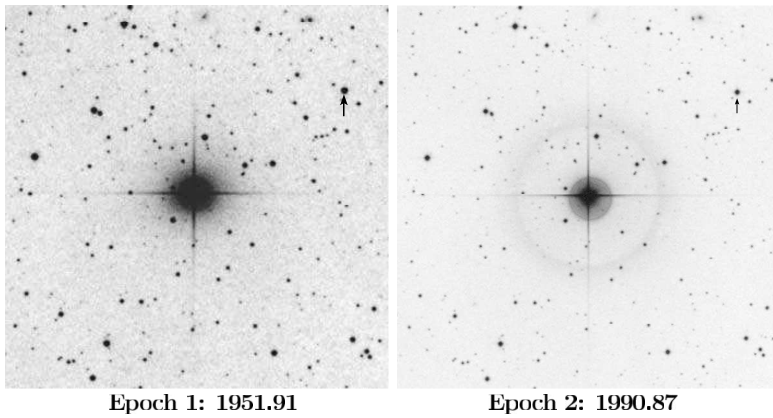

Fig. 3.—New stellar companion to exoplanet host HD 38529. The 10′ square DSS images have north up and east to the left. The companion, marked by arrows, is at an angular separation of 284″ at 305° from the primary, which is at the center of the images.

systemic velocity of -27.5 km s^{-1}, from Marcy & Moore (1989). HD 38529B's radial velocity was measured to be 26.26 ± 0.10 km s^{-1}. This is roughly consistent with the primary's radial velocity of 30.21 km s^{-1} (Nidever et al. 2002), and the odds of two unassociated stars having such similar velocities are low. However, discrepancies in radial velocities and photometric distances could indicate that the new companion is a double. The projected separation of the primary to the new companion(s) is $\sim$12,000 AU, which is extreme for a gravitationally bound system, although Poveda et al. (1994) listed a few wide binaries with even greater separations. This primary also has a *Hipparcos* G flag listing, which was recently used by Reffert & Quirrenbach (2006) to conclude that the substellar companion "c" is actually a brown dwarf of mass $37^{+36}_{-19}\,M_{\rm J}$.

HD 41004.—A companion is listed in WDS and annotated in *Hipparcos* with a C flag, indicating a linear relative motion of components, implying either an orbital period that is several times the length of the *Hipparcos* observing interval (3.3 yr) or stars that are not physically linked. At a separation of 0″.5 and a $\Delta m = 3.67$ (from *Hipparcos*), the identification of a close companion is difficult, but there are other such *Hipparcos* observations (similar separation and Δm) that were independently confirmed. For example, T. J. J. See measured a close large Δm pair, known as SEE 510 (HIP 86228), with the Lowell 24 inch (0.61 m) telescope in 1896 (See 1897). This pair, lost for nearly 100 yr, was recovered by *Hipparcos* at about the same position (0″.2, $\Delta m = 1.8$). While SEE 510 is not morphologically identical to HD 41004, we believe that it is comparably difficult, and so we accept the *Hipparcos* identification of a companion to HD 41004. This system was mentioned in Eggenberger et al. (2004) as a stellar companion in an exoplanet system. Further, Zucker et al. (2003) listed the radial velocity for the primary as 42.5 ± 0.01 km s^{-1} and found the companion to be a double, with a velocity range of 34–48 km s^{-1} ($\pm$0.56 km s^{-1}) over 103 observations. They derived an orbital solution for the BC pair, concluding that the orbit is nearly circular with $a \sin i = 0.016$ AU and that the low-mass companion has a minimum mass of 18.4$M_{\rm J}$. Zucker et al. (2004) derived orbital elements of the possible M dwarf–brown dwarf pair and concluded that this is a unique system with each stellar component of a visual binary having a low-mass companion in orbit around it: one a planet, and the other a possible brown dwarf. Note that the projected separation between A and B is just 22 AU, similar to the separation of the Sun and Uranus.

HD 40979.—This CPM pair is clearly identified in DSS images. The primary is 33 pc away with $\mu = 0''.179$ yr^{-1} at 148° (from *Hipparcos*). The companion, BD +44 1351, has a very similar $\mu = 0''.179$ yr^{-1} at 148° from Lepine & Shara (2005) and 0″.180 yr^{-1} at 148° from Hog et al. (1998). Halbwachs (1986) identified this CPM pair, listing the companion as a K5 star. Eggenberger et al. (2004) identified this as a stellar companion to a planetary system, noting that physical association of this pair has been confirmed via radial velocity measurements. However, our plate photometric distance estimate to the companion is 15.2 ± 4.0 pc (based on only three colors), not a very good match with the primary, although the error is large. This discrepancy could be due to the poor quality of the photometric distance estimate (due to the blue colors of the companion) or perhaps because the companion is an unresolved double.

HD 46375.—WDS lists this 9″.4 separation companion at 308°. We took short exposure frames at CTIO in 2004 September, which identified a companion at a separation of 10″ at 310°, consistent with the WDS observation. The first published resolution of this pair made by Soulie (1985) in 1984 has also been confirmed by 2MASS images. Reanalysis of Astrographic Catalogue data (Urban et al. 1998) has added an observation at about the same secondary position in 1932, thereby confirming that it has the same proper motion. Our CCD photometric distance estimate of 26.4 ± 6.0 pc is within 2 σ of the primary's distance of 33.4 pc from *Hipparcos*. We therefore conclude that this is a physical pair. This work is the first identification of this as a stellar companion to a planetary system.

HD 75289.—This CPM candidate was detected by Mugrauer et al. (2004a) and confirmed by their photometry and spectroscopy. While the companion is seen in the epoch 2 DSS image, CPM could not be established by our method due to saturation of the region around the primary in the epoch 1 image.

HD 75732.—This CPM pair is easily identified in DSS images and matches entries in WDS, CNS, and Duquennoy &

Mayor (1991). The primary has $\mu = 0''.539$ yr^{-1} at 244° and $\pi = 0''.07980 \pm 0''.00084$, from *Hipparcos*. Our CCD photometric distance estimate to the companion is 8.7 ± 1.4 pc, a match within 3 σ. The companion's $\mu = 0''.540$ yr^{-1} at 244° and $\pi = 0''.0768 \pm 0''.0024$ from the Yale Parallax Catalog (van Altena et al. 1995) and $0''.0757 \pm 0''.0027$ from Dahn et al. (1988) are all consistent with the primary's. This system is listed in Eggenberger et al. (2004) as a stellar companion to a planetary system. The primary star, more commonly known as 55 Cnc, has four reported planets, so this system is the most extensive solar system with a stellar companion, which is at a projected distance of more than 1000 AU. The discrepancy in photometric distance could hint that the companion is an unresolved double.

HD 80606.—This CPM pair is easily identified in DSS images and matches entries in WDS and *Hipparcos*. The primary's $\mu = 0''.047$ yr^{-1} at 82° and $\pi = 0''.01713 \pm 0''.00577$, from *Hipparcos*. The parallax has a large error due to the close companion. The companion is HD 80607, spectral type G5, $\mu = 0''.043$ yr^{-1} at 79°, and *Hipparcos* lists an identical parallax. This companion was listed by Eggenberger et al. (2004) as a stellar companion to a planetary system.

HD 89744.—This companion was reported as a candidate by Wilson et al. (2001) based on spectroscopic observations, and they identified it as a massive brown dwarf of spectral type L0 V. Companionship was subsequently confirmed astrometrically by Mugrauer et al. (2004b). This faint companion is not seen in the DSS images.

HD 99492.—This CPM pair is easily identified in DSS images and matches entries in WDS, *Hipparcos*, and CNS. Component B (the exoplanet host) has $\mu = 0''.755$ yr^{-1} at 285° and $\pi = 0''.05559 \pm 0''.00331$, from *Hipparcos*. Component A is HD 99491 with spectral type K0 IV, $\mu = 0''.749$ yr^{-1} at 284°, and $\pi = 0''.05659 \pm 0''.00140$, from *Hipparcos*. These match HD 99492's values well and confirm the pair as physical.

HD 114729.—This CPM candidate was detected recently by Mugrauer et al. (2005) and confirmed by their photometry and spectroscopy. It could not be detected using DSS frames due to saturation of the region around the primary.

HD 114762.—This close companion was discovered using high-resolution imaging (Patience et al. 2002). It was also mentioned by Eggenberger et al. (2004) as a stellar companion to a planetary system. The "planet," with $M \sin i = 11.0 M_J$, may in fact be a star in a low-inclination orbit (Cochran et al. 1991; Fischer & Valenti 2005).

HD 120136.—This close companion is listed in WDS (53 observations), CNS, and Duquennoy & Mayor (1991). The primary's $\mu = 0''.483$ yr^{-1} at 276° from *Hipparcos*. CNS lists the companion as GJ 527B, and SIMBAD gives its $\mu = 0''.480$ yr^{-1} at 274°, a good match to the primary's. This system has been recognized as a stellar companion to an exoplanet system (Patience et al. 2002; Eggenberger et al. 2004).

HD 142022.—This CPM pair (GJ 606.1AB) is easily identified in DSS images and matches entries in WDS and CNS. The companion's spectral type is K7 V. The NLTT catalog lists identical μ for both components, $\mu = 0''.320$ yr^{-1} at 269° (Luyten 1979).

HD 147513.—This companion is listed in CNS and was the first white dwarf found in an exoplanet system (Mayor et al. 2004). The primary's $\mu = 0''.073$ yr^{-1} at 87° and $\pi = 0''.07769 \pm 0''.00086$, from *Hipparcos*. The companion is HIP 80300, type DA2 (Wegner 1973), with matching *Hipparcos* values of $\mu = 0''.076$ yr^{-1} at 90° and $\pi = 0''.07804 \pm 0''.00240$.

HD 178911.—This is a triple-star system with one known planet. The wide CPM pair (AC-B) is clearly seen in DSS images. The $6.3 M_J$ planet orbits HD 178911B, while HD 178911AC is a close binary, first resolved by McAlister et al. (1987b) with the Canada-France-Hawaii Telescope (CFHT). This pair has since been resolved 10 more times, most recently with the 6 m telescope of the Special Astrophysical Observatory in Zelenchuk in 1999 (Balega et al. 2004). Hartkopf et al. (2000) present an orbital solution with a 3.5 yr period based on speckle observations, and Tokovinin et al. (2000) present a full orbital solution using spectroscopic and interferometric data. The multiplicity of this system has been previously identified (Zucker et al. 2002; Eggenberger et al. 2004). From *Hipparcos*, HD 178911AC's $\mu = 0''.200$ yr^{-1} at 14° and $\pi = 0''.02042 \pm 0''.00157$ and the companion's $\mu = 0''.203$ yr^{-1} at 19° and $\pi = 0''.02140 \pm 0''.00495$, a match within the errors, confirming a physical association.

HD 186427.—This is a triple-star system with one known planet. The wide CPM pair (AC-B) is clearly seen in DSS images. The planet orbits 16 Cyg B (HD 186427), while 16 Cyg A (HD 186408) is a close binary, first resolved by Turner et al. (2001) with the AO system on the Hooker 100″ telescope and independently confirmed by IR imaging by Patience et al. (2002) with the Keck 10 m and Lick 3 m. In the five total observations, the position of the secondary has not changed much. However, they span less than 2 yr of time and little motion would be expected at a projected separation of 73 AU. The multiplicity of this system has been previously identified (Patience et al. 2002; Lowrance et al. 2002; Eggenberger et al. 2004). From *Hipparcos*, 16 Cyg A's $\mu = 0''.217$ yr^{-1} at 223° and $\pi = 0''.04625 \pm 0''.00050$ and the planet host's $\mu = 0''.212$ yr^{-1} at 220° and $\pi = 0''.04670 \pm 0''.00052$, a match within the errors, confirming a physical association.

HD 188015.—This new companion was detected by us as a CPM candidate and confirmed via CCD photometry. The primary's $\pi = 0''.01900 \pm 0''.00095$ and $\mu = 0''.106$ yr^{-1} at 149°, from *Hipparcos*. The companion, 13″ away from the primary at 85°, does not have proper motion listed in SuperCOSMOS or NLTT, but our CCD photometric distance of 46.9 ± 9.5 pc matches the primary's distance within 1 σ and hence confirms this as a companion. Figure 4 includes two DSS images showing the primary and the companion.

HD 190360.—This CPM pair is easily identified in DSS images and matches entries in WDS and CNS. The primary is GJ 777A with spectral type G7 IV–V and $\mu = 0''.861$ yr^{-1} at 127° from *Hipparcos*. The companion is GJ 777B with spectral type M4.5 V and $\mu = 0''.860$ yr^{-1} at 127° (Lepine & Shara 2005). Our plate photometric distance estimate of 18.5 ± 6.2 pc is a good match with the primary's trigonometric parallax distance of 15.9 pc. This system has been recognized as a binary and as an exoplanet primary with a stellar companion (Allen et al. 2000; Naef et al. 2003; Eggenberger et al. 2004).

HD 195019.—WDS is the only source listing this close binary at a separation of 3″.5 at 330°. The close pair, first resolved by Hough (1887) with an 18 inch refractor, has moved 7° in position angle and closed in from 4″.5 to 3″.5 in separation in 12 observations over 107 yr. This transition has not been smooth, no doubt due to $\Delta m = 4$, making observations a challenge. The typical measurement errors of micrometry, coupled with slow motion, make characterization difficult. It was identified as a binary in Allen et al. (2000) and recognized as a stellar companion to an exoplanet system in Eggenberger et al. (2004).

HD 196050.—This CPM candidate was detected recently by Mugrauer et al. (2005) and confirmed by their photometry and spectroscopy. It could not be detected using DSS frames due to saturation of the region around the primary.

HD 213240.—This CPM pair was identified by us using DSS images. The primary's $\mu = 0''.236$ yr^{-1} at 215° and $\pi = 0''.02454 \pm 0''.00081$, from *Hipparcos*. The companion's

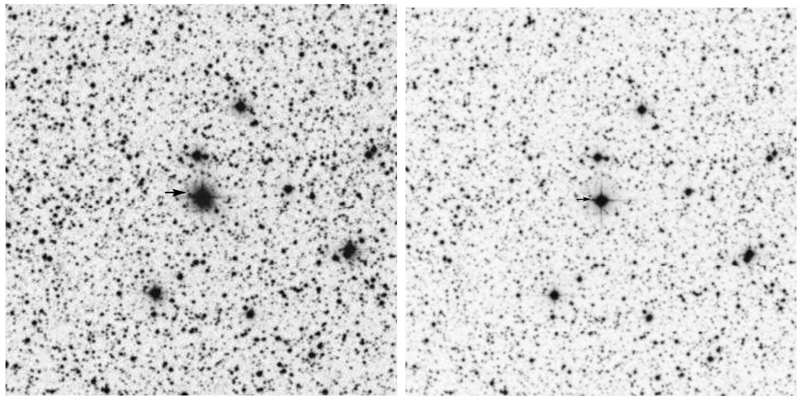

FIG. 4.—New stellar companion to exoplanet host HD 188015. The 10′ square DSS images have north up and east to the left. The companion, marked by arrows, is at an angular separation of 13″ at 85° from the primary, which is the bright source at the center of the images.

$\mu = 0''.229$ yr^{-1} at 214° from SuperCOSMOS is a good match. Our CCD photometric distance of 41.8 ± 6.5 pc is consistent with our spectral type identification of M5.0 V and is a good match to the primary's trigonometric parallax distance of 40.8 pc. This new companion identification in an exoplanet system was recently reported by Mugrauer et al. (2005) during the writing of this paper.

HD 219449.—A CPM companion is easily detected in the DSS images and is matched by WDS and CNS entries. WDS lists the secondary as a tight binary (0″.4 separation at 101°). The primary's $\mu = 0''.369$ yr^{-1} at 93° and $\pi = 0''.02197 \pm 0''.00089$, from *Hipparcos*. The companion binary has $\mu = 0''.377$ yr^{-1} at 91° from NLTT and 0″.385 yr^{-1} at 96° from Zacharias et al. (2004), both good matches to the primary. NLTT also lists the companion's spectral type as K8 V. Our CCD photometric distance of 29.9 ± 4.7 pc is for the BC pair, and we predict an actual distance of 42.4 pc (assuming identical spectral types), which is a good match to the primary (45.5 pc). Radial velocities from Wilson (1953) are -26.4 ± 0.9 km s^{-1} for the primary and -25 ± 5 km s^{-1} for the secondary, also a match within the errors. Our approximate spectral identification as an early K type is consistent with the photometric distances. This work recognizes, for the fist time, that this exoplanet system resides in a triple-star system.

HD 222404.—This companion is listed in *Hipparcos* with a G flag, indicating a close astrometric binary. While some speckle searches have failed to detect a companion (e.g., Mason et al. 2001), the companion has been detected via radial velocity efforts and identified as a stellar companion in an exoplanet system (Campbell et al. 1988; Griffin et al. 2002; Eggenberger et al. 2004). The semimajor axes of the planet and stellar companions with respect to the primary place them at Sun–Mars and Sun–Uranus separations, respectively.

HD 222582.—This CPM pair is easily seen in DSS images and is listed in the WDS. The primary's $\mu = 0''.183$ yr^{-1} at 233° and $\pi = 0''.02384 \pm 0''.00111$, from *Hipparcos*. The secondary's $\mu = 0''.180$ yr^{-1} at 231° from NLTT, 0″.186 yr^{-1} at 230° from SuperCOSMOS, and 0″.187 yr^{-1} at 232° from Zacharias et al. (2004) are all good matches to the primary. Our CCD photometric distance of 32.1 ± 5.0 pc matches the primary's distance of 42.0 pc within 2 σ. Our spectral type of M3.5 V is consistent with the photometric distance estimates. This pair, resolved by Luyten in 1960, was noted to have a common proper motion. This work confirms the gravitational relationship via CPM, photometry, and spectroscopy and is the first identification of this stellar companion to an exoplanet system.

5.1.2. *Candidate Companion Systems*

HD 8673.—WDS is the only source listing a close companion, at 0″.1 separation. Resolved by Brian Mason in 2001 as part of a survey of nearby G dwarfs for duplicity, this unpublished observation has yet to be confirmed. The projected stellar separation of 3.8 AU is just over twice the planet/brown dwarf projected separation of 1.6 AU and dynamical instability is likely. Alternatively, given the large $M \sin i = 14M_J$ for the "planet," it is possible that it is actually a star in a near face-on orbit ($i \leq 10°$) and that the radial velocity and speckle observations are of the same object.

HD 16141.—This CPM candidate was recently detected by Mugrauer et al. (2005) at a separation of 6″.2, and they plan follow-up observations to confirm it. We could not detect the companion using DSS frames due to saturation of the region around the primary.

HD 111232.—This companion is mentioned only in *Hipparcos* and is listed with a G flag, indicating that the proper motion was best fitted with higher order terms. Mason et al. (1998) conducted a specific search for a companion using optical speckle but did not find any. Their effort should have picked up companions with $\Delta V \lesssim 3$ and separations 0″.035–1″.08.

HD 150706.—This companion is mentioned only in *Hipparcos* and is listed with a G flag, indicating that the proper motion was best fitted with higher order terms. Halbwachs et al. (2003) reported this as a single star based on two CORAVEL radial velocity surveys that yielded statistical properties of main-sequence binaries with spectral types F7–K and with periods up to 10 yr.

HD 169830.—A candidate companion was detected by Kevin Apps as a close 2MASS source with 11″ separation at 265° (K. Apps 2005, private communication). Our CCD photometric distance estimate for the companion is 29 ± 23 pc, consistent with the primary's distance of 36 pc, but the large error in our estimate prevents confirmation. The large error is likely due to the uncertainty in our and 2MASS photometry, caused by the close, bright primary and the proximity of the companion to the primary's diffraction spike. While 2MASS lists errors of 0.04 mag for JHK_s, it notes that the photometry is contaminated by a nearby bright source. Also, the J magnitude from DENIS is 0.36 mag brighter than the 2MASS value, indicating a larger uncertainty. The low proper motion (0."015 yr^{-1}) of the primary prevents confirmation via CPM. While we believe that the evidence strongly indicates that this is a true companion, we cannot confirm it until we obtain a spectrum or other conclusive evidence.

HD 217107.—Only WDS lists this close companion with 0."3 separation at 156°. Proper motion of the primary is not detectable in DSS images. This pair has been resolved only twice (McAlister et al. 1987a; Mason et al. 1999) 15 yr apart, and the lack of additional resolutions of this bright pair seems to indicate that a large magnitude difference may be preventing additional detections. Given the two reported planets with $a \sin i = 0.1$ and 4.3 AU, this companion at a projected separation of just 6 AU would likely induce dynamical instability. Explanations for this include the possibility that this is an unrelated star with a chance alignment and/or that the wider "planet" is actually a stellar companion with a face-on orbit.

5.2. *Refuted Candidates: CPM Alone Does Not Confirm Companionship*

As CPM is often used to detect gravitationally bound companions, we list here five exceptions that, upon follow-up analyses, turned out to be unrelated field stars rather than true companions. In three of these instances (HD 33636, HD 41004, and HD 72659) we found proper motions in DSS plates to be an acceptable match by eye, but photometric distances indicated that each candidate was a distant field star. In the cases of BD −10 3166 and HD 114783, photometric distances did not provide a conclusive answer, but plotting these on an M_V versus $B - V$ curve of a sample of *Hipparcos* stars allowed us to refute them.

BD −10 3166 is the only exoplanet primary without a *Hipparcos* parallax. We derived a CCD photometric distance of 66.8 ± 10.0 pc, but that is based on just one color because the object is on the blue end of the M_{K_s}-color relations described in Henry et al. (2004). The companion candidate, LP 731-076, is 17″ from the primary at 217° (in the DSS1, epoch 1983.29 image) and appears to have a matching proper motion. The two stars were identified by Luyten (1978) as a CPM pair and recently recovered in SuperCOSMOS data by R. Jaworski (2005, private communication). In SuperCOSMOS, the primary's $\mu = 0.''189$ yr^{-1} at 252° and the candidate's $\mu = 0.''202$ yr^{-1} at 242°. The candidate has a published photometric distance of 11.6 ± 0.8 pc (Reid et al. 2002), which is consistent with our photometric distance estimate of 12.5 ± 2.0 pc and our spectral type listed in Table 4. In order to get a better distance estimate to the primary, we plotted 285 stars from *Hipparcos* on an M_V versus $B - V$ diagram. The stars were selected based on distance (parallax greater than 0."05), quality of parallax (error less than 10%), luminosity class (main sequence only), and $B - V$ value of greater than 0.5. Fitting the primary's $B - V$ of 0.84 from Ryan (1992) to the least-squares fit curve through the *Hipparcos* data yields a distance estimate of 68 pc, consistent with our photometric distance estimate and too large to be associated with the candidate companion. This is an interesting example of a close (17″ separation) CPM pair for which distance estimates to both components are of the same order of magnitude, but the components seem to be unrelated.

HD 33636 has $\mu = 0.''227$ yr^{-1} at 127° and $\pi = 0.''03485 \pm 0.''00133$ (29 pc) from *Hipparcos*. The faint CPM candidate at a separation of 220″ at 250° (in the DSS POSS2/UKSTURed, epoch 1990.81 image) was refuted by us after obtaining a CCD photometric distance of 739 ± 162 pc. Our spectrum, although noisy, allows us to estimate the spectral type to be M1.0 V, which indicates a large distance consistent with the photometric estimate.

HD 41004 has $\mu = 0.''078$ yr^{-1} at 327° and $\pi = 0.''02324 \pm 0.''00102$ (43 pc), from *Hipparcos*. The faint CPM candidate at a separation of 145″ at 335° (in the DSS POSS2/UKSTURed, epoch 1993.96 image) was refuted by us after obtaining a CCD photometric distance of 557 ± 103 pc. We estimate the spectral type to be M0.5, although the luminosity class is uncertain: it could be a dwarf or a subdwarf. The candidate's $\mu = 0.''046$ yr^{-1} at 6° from SuperCOSMOS is not a good match to the primary.

HD 72659 has $\mu = 0.''150$ yr^{-1} at 229° and $\pi = 0.''01947 \pm 0.''00103$ (51 pc), from *Hipparcos*. The candidate, at a separation of 195″ at 165° (in the DSS POSS2/UKSTURed, epoch 1992.03 image), was refuted by us after obtaining a CCD photometric distance of 369 ± 99 pc. Our spectral identification as M3.0 V is consistent with this photometric distance. SuperCOSMOS lists the CPM candidate's $\mu = 0.''066$ yr^{-1} at 199°, showing that proper motion is not a good match.

HD 114783 is another CPM pair that looks like it may be physical but is not. From *Hipparcos*, the primary has $\mu = 0.''138$ yr^{-1} at 274° and from SuperCOSMOS, the candidate companion (at a separation of 240″ at 47° in the DSS POSS2/UKSTURed, epoch 1996.23 image) has $\mu = 0.''184$ yr^{-1} at 281°. The primary's distance from the *Hipparcos* parallax is 20.4 pc. Our plate photometric distance estimate for the companion is 20.2 ± 5.2 pc based on only three colors. However, using CCD photometry, we get a distance of 54.0 ± 9.3 pc, based on only two colors. The candidate companion is CCDM J13129−0213AB, a binary (listed in the WDS with a separation of 2."0 at 28°), and hence its actual distance is greater than photometrically indicated. We plotted the primary on the M_V versus $B - V$ diagram using *Hipparcos* data as described above, and it falls close to the main-sequence fit, indicating that it is likely a single star. The candidate companion, based on its $B - V$ of 1.10, yields a distance of 36 pc, using the *Hipparcos* plot, but its actual distance will be greater because it is a binary. Our spectra for the two stars show very similar absorption lines, although the continuum seems to indicate that the candidate companion is slightly redder. Given that the spectral types are close and that the candidate companion is a binary while the primary appears to be single, we can only explain the large ΔV (primary $V = 7.56$, and candidate companion $V = 9.78$) by adopting significantly different distances to the two stars. Hence, we conclude that this is not a gravitationally bound pair, despite the compelling proper-motion match.

6. DISCUSSION

Our findings indicate that 30 (23%) of the 131 exoplanet systems have confirmed stellar companions and 6 more (5%) have candidate companions. Given the constraints of our search (any new companions we detected had to be widely separated from primaries with high proper motion), these numbers should be regarded as lower limits. This point is confirmed by a recent paper, Mugrauer et al. (2005), which reported four new companions in exoplanet systems, of which we had independently identified only one (HD 213240B). Several interesting properties are revealed by this comprehensive assessment.

Three of the exoplanet systems (HD 178911, 16 Cyg B, and HD 219449) are stellar triples and are arranged similarly: a

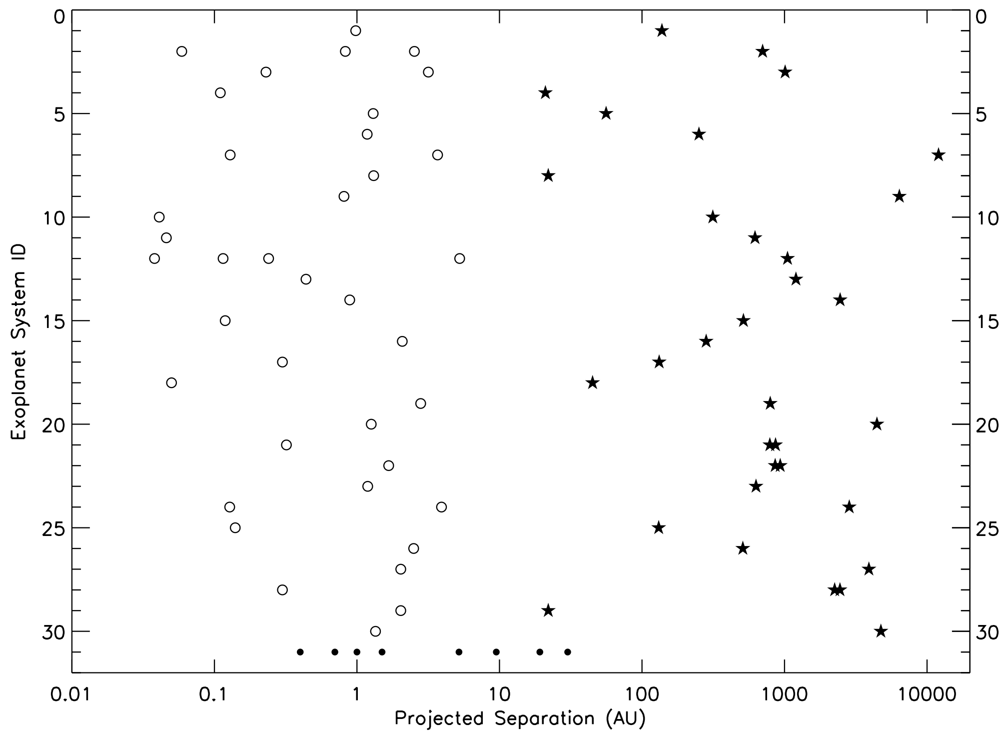

Fig. 5.—Orbits of planets and stars in exoplanet systems with stellar companions. The exoplanet host stars are at a position of 0 AU. Open circles represent planets, and stars represent stars. Points will tend to move right because of orbital inclination and projection effects. Separations between the components of the three binary companions are exaggerated to be able to distinguish the binary components on the plot. For comparison, the positions of the eight planets of our solar system are shown at the bottom as filled circles.

single planet orbits close to one star and there is a distant, tight binary. In each system, the three stars are all of the same spectral class (G for HD 178911 and 16 Cyg, and K for HD 219449). We find it curious that all three triple systems contain stars of comparable mass (i.e., systems such as a G dwarf exoplanet host with an M dwarf binary are not seen). Could this be due to a selection effect (i.e., faint companions are not as well studied for multiplicity), or does this say something about the angular momentum distribution in star-forming regions? Only a comprehensive survey of all companions for duplicity can lead us to an answer.

It is interesting to note that recent exoplanet discoveries are predominantly found in single-star systems. Of the first 102 radial velocity–detected exoplanet systems, 26 (26%) have confirmed stellar companions. In contrast, only 4 (14%) of the latest 29 systems have confirmed stellar companions. Even though we are dealing with small number statistics, we believe that this change is significant and worthy of further examination. Our first inclination was that recent planet detections are at larger projected semimajor axes and hence favor single systems because stellar companions would have to be even farther out to provide the uncorrupted "single" systems sought by radial velocity programs. However, we found no correlation between the timing of exoplanet reporting and its projected semimajor axis. Thus, we are not able to explain this curiosity at this point and simply identify it for further examination.

Exoplanet hosts are deficient in having stellar companions when compared to a sample of field stars. Our updated results for stellar counts in the exoplanet sample yield a single : double : triple : quadruple percentage of 79:21:2:0 for confirmed systems, and 72:24:4:0 considering candidates. While these are lower limits for multiplicity, they are significantly lower than the Duquennoy & Mayor (1991) results of 57 : 38 : 4 : 1 for multiples with orbits, and 51 : 40 : 7 : 2 considering candidates. This is certainly due in part to the fact that planet searches specifically exclude known close binaries from their samples (e.g., Vogt et al. 2000) and further eliminate any new binaries detected via radial velocity. We currently do not have enough detailed information about the exoplanet search target selection process to say whether the different multiplicity ratios are entirely due to selection effects or are indicative of planetary disk instability and reduced planet formation in binary-star systems.

6.1. *Planetary and Stellar Orbits in Multiple-Star Systems*

Figure 5 shows the $a \sin i$ of planetary companions and projected separations of the stellar companions for the 30 confirmed exoplanets that reside in multiple-star systems. The *Y*-axis shows

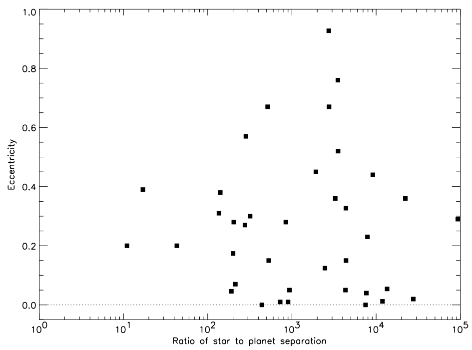

Fig. 6.—Eccentricity of planetary orbits as a function of proximity of the stellar companion. The ratio is computed using projected stellar separation and $a \sin i$ of the planetary orbit.

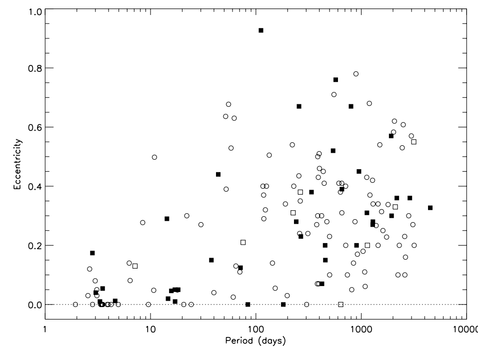

Fig. 7.—Period-eccentricity diagram for planets orbiting single stars (*open circles*) and planets in systems with more than one star (*open squares*: candidate multiplicity; *filled squares*: confirmed multiplicity).

the sequence number of the exoplanet system as listed in column (1) of Table 2. The figure clearly indicates the presence of separate planetary and stellar orbit regimes for the data currently available. All planets are within 6 AU, and all stars are at a projected separation of greater than 20 AU from the exoplanet host. Note that all points in the figure can potentially move right because (1) planets are plotted at a separation of $a \sin i$ and (2) stars are plotted based on their projected separations (although a few could move left if they have been caught near apastron in their orbits). The continued search for wider orbit planets will answer the question of whether this is simply due to selection effects or if this says something significant about planetary disk truncation in multiple-star systems.

55 Cnc (HD 75732), an extensive extrasolar system with four reported planets, has the widest projected planetary orbit with an $a \sin i$ of 5.3 AU. It is noteworthy that such an extensive exoplanet system also has a stellar companion, at a projected separation of 1050 AU. This provides direct evidence of the stability of protoplanetary disks in multiple-star systems such as to allow formation and sustenance of multiple planets, at least as long as the separation between the stars is sufficiently large. This system can also provide an observational constraint for evaluating theoretical models of disk stability and solar system evolution.

The smallest projected separation for a stellar companion is 21 AU for GJ 86, closely followed by 22 AU for HD 41004 and γ Cep. Each system has only one reported planet, with $a \sin i$ of 0.1, 1.3, and 2.0 AU, respectively. This may be evidence that a sufficiently close stellar companion will disrupt the protoplanetary disk, truncating planet formation at a few AU from the primary.

Several studies have investigated the theoretical stability of planetary orbits in multiple-star systems (e.g., Holman & Wiegert 1999; Benest & Gonczi 2003), deriving ratios of orbital semimajor axes of the planet and stellar companions for various values of mass ratio and eccentricity of the stellar orbits. Our work provides observational constraints based on all known exoplanets in multiple-star systems. Of the 30 confirmed exoplanets in multiple-star systems, only 3 have a ratio of stellar to planetary projected separation of less than 100. The lowest ratio is 11, for γ Cep (HD 222404). Although numerical simulations demonstrate the stability of orbits for much smaller separation ratios [e.g., for $m_2/(m_1 + m_2) = 0.5$ and $e = 0.1$, the minimum ratio of stellar and planetary orbital semimajor axes is about 4 from Holman & Wiegert 1999], no planets have yet been observed in this regime. This could be attributed to the selection effect of close binaries being excluded from planet searches, as described above. However, this could also provide evidence for protoplanetary disk truncation by a close stellar companion, preventing planet formation in systems with separation ratios close to the limits permitted by numerical simulations.

Every exoplanet system so far discovered in a multiple-star system has an S-type (satellite-type) orbit, where the planet orbits one of the stars. This is not surprising because current radial velocity searches for exoplanets exclude close binaries (e.g., Vogt et al. 2000). While the formation and stability of planets in P-type (planet-type) orbits, where a planet orbits the center of mass of a binary- or multiple-star system, have been theoretically demonstrated (Holman & Wiegert 1999; Boss 2005; Musielak et al. 2005), they have not yet been observationally supported. However, Correia et al. (2005) have raised the interesting possibility that the $2.4M_J$ outer planet around HD 202206 may in fact have formed in a circumbinary disk around the primary and the closer $17M_J$ minimum-mass object.

6.2. *Stellar Companions Might Influence Eccentricity of Planetary Orbits*

Eccentricities of exoplanet orbits are significantly higher than those of planets in our solar system (Marcy et al. 2005a). Takeda & Rasio (2005) investigated whether the Kozai mechanism can explain this entirely and concluded that other effects are also at play. We investigated the potential impact of close stellar companions on the eccentricity of planetary orbits, as these would have a greater gravitational influence on the planet's orbit and potentially reduce the period of Kozai cycles. Figure 6 shows the eccentricity of the planetary orbits as a function of the ratio of projected stellar separations to the $a \sin i$ of planetary orbits and does not conclusively demonstrate any relationship. However, even though three data points do not provide conclusive evidence, it is interesting to note that the systems with ratios under 100 have a minimum eccentricity of 0.2, while larger ratio systems have lower eccentricities.

We also looked at the relationship between period and eccentricity of planetary orbits in systems with and without stellar companions. Figure 7 shows the eccentricity of planetary orbits versus the orbital period. Planet orbits in systems with confirmed stellar companions are represented by filled squares, orbits with candidate stellar companions are represented by open squares, and orbits in single-star systems are denoted by open circles. Udry et al. (2004) and Eggenberger et al. (2004) presented similar plots and concluded that all of the planets with a period $P \lesssim 40$ days orbiting in multiple-star systems have an eccentricity smaller than 0.05, whereas longer period planets found in multiple-star systems can have larger eccentricities. Our updated results show that this conclusion is no longer strictly true. The latest planet reported around 55 Cnc, designated with suffix e, has a period of 2.81 days and an eccentricity of 0.17. Also, we report HD 38529 as a multiple-star system, which was assumed to be a single-star system in Udry et al. (2004). Planet HD 38529b has a period of 14.31 days and an eccentricity of 0.29. It appears that single-star and multiple-star planetary systems have similar period-eccentricity relationships.

7. CONCLUSIONS

Our comprehensive investigation of 131 exoplanet systems reveals that 30 (23%) of these have stellar companions, an increase from 15 reported in previous such comprehensive efforts (Eggenberger et al. 2004; Udry et al. 2004). We report new stellar companions to HD 38529 and HD 188015 and identify a candidate companion to HD 169830. Our synthesis effort, bringing together disparate databases, recognizes, for the first time, five additional stellar companions to exoplanet hosts, including one triple system. A by-product of our CPM investigation is the determination that 20 of the WDS entries for exoplanet hosts are not gravitationally bound to their ''primaries'' but are chance alignments in the sky. Some interesting examples in the inventory of multiple-star exoplanet systems include the following: (1) at least three and possibly five exoplanet systems are stellar triples (see § 6); (2) three systems (GJ 86, HD 41004, and γ Cep) have planets at roughly Mercury–Mars distances and potentially close-in stellar companions at projected separations similar to the distance between the Sun and Uranus ($\sim$20 AU); and (3) two systems (GJ 86 and HD 147513) have white dwarf companions. These results show that planets form and survive in a variety of stellar multiplicity environments. We hope that this compendium of stellar multiples in exoplanet systems will provide a valuable benchmark for future companion searches and exoplanet system analyses.

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The Visual Orbit σ^2 Coronae Borealis

The following pages reproduce the Astrophysical Journal publication, Raghavan et al. (2009), that, based on the work done as part of this thesis, presented a revised spectroscopic orbit and a new visual orbit for σ^2 CrB.

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THE VISUAL ORBIT OF THE 1.1 DAY SPECTROSCOPIC BINARY σ^2 CORONAE BOREALIS FROM INTERFEROMETRY AT THE CHARA ARRAY

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ABSTRACT

We present an updated spectroscopic orbit and a new visual orbit for the double-lined spectroscopic binary σ^2 Coronae Borealis (CrB) based on radial velocity measurements at the Oak Ridge Observatory in Harvard, MA and interferometric visibility measurements at the Center for High Angular Resolution Astronomy (CHARA) Array on Mount Wilson in California. σ^2 CrB is composed of two Sun-like stars of roughly equal mass in a circularized orbit with a period of 1.14 days. The long baselines of the CHARA Array have allowed us to resolve the visual orbit for this pair, the shortest-period binary yet resolved interferometrically, enabling us to determine component masses of 1.137 ± 0.037 $M_\odot$ and 1.090 ± 0.036 $M_\odot$. We have also estimated absolute *V*-band magnitudes of $M_V(\text{primary}) = 4.35 \pm 0.02$ and $M_V(\text{secondary}) = 4.74 \pm 0.02$. A comparison with stellar evolution models indicates a relatively young age of 0.1–3 Gyr, consistent with the high-Li abundance measured previously. This pair is the central component of a quintuple system, along with another similar-mass star, σ^1 CrB, in a ~730-year visual orbit, and a distant M-dwarf binary, σ CrB C, at a projected separation of ~10′. We also present differential proper motion evidence to show that components C & D (ADS 9979C & D) listed for this system in the Washington Double Star Catalog are optical alignments that are not gravitationally bound to the σ CrB system.

Key words: binaries: spectroscopic – stars: fundamental parameters – stars: individual (σ^2 Coronae Borealis) – techniques: interferometric

1. INTRODUCTION

σ Coronae Borealis (CrB) is a hierarchical multiple system 22 pc away. Its primary components, σ^1 CrB (HR 6064; HD 146362) and σ^2 CrB (HR 6063; HD 146361), are in a visual orbit with a preliminary period of ~900 years (Scardia 1979), of which the latter is an RS CVn binary with a circularized and synchronized orbit of 1.139-day period (Strassmeier & Rice 2003, SR03 hereafter). In addition to these three solar-type stars, the Washington Double Star Catalog[6] (WDS) lists three additional components for this system. WDS components C and D were resolved 18″ away at 103° in 1984 (Popović 1986) and 88″ away at 82° in 1996 (Courtot 1996), respectively. We will show in Section 6 that both these components are optical alignments that are not gravitationally bound to the σ CrB system. Finally, WDS component E (σ CrB C, HIP 79551), which was resolved 635″ away at 241° in 1991 by *Hipparcos* (Perryman & ESA 1997), was identified as a photocentric-motion binary by Heintz (1990). The parallax and proper motion listed for this star in van Leeuwen (2007), the improved *Hipparcos* results based on a new reduction of the raw data, match the corresponding measures for σ^2 CrB within the errors, confirming a physical association.

SR03 presented photometric evidence in support of a rotation period of 1.157 ± 0.002 days for both components of σ^2 CrB, the central pair of this system. They explained the 0.017-day difference between the rotation and orbital periods as differential surface rotation. Bakos (1984) estimated an orbital inclination of 28°, assuming component masses of 1.2 $M_\odot$ based on spectral types. SR03 subsequently adopted this inclination to obtain component masses of $1.108 \pm 0.004\ M_\odot$ and $1.080 \pm 0.004\ M_\odot$, but these masses are based on circular reasoning, and the errors are underestimated as they ignore the uncertainty in inclination. Several spectroscopic orbits have been published for this pair (Harper 1925; Bakos 1984; Duquennoy & Mayor 1991; SR03), enabling the spectroscopic orbital elements to be well constrained. We present an updated spectroscopic solution based on these prior data and our own radial velocity measurements (Sections 2.1 and 4.1). Our visual orbit leverages these spectroscopic solutions and derives all orbital elements for this binary (Section 4.2), leading to accurate component masses (Section 5.1).

This work utilizes a very precise parallax measure for this radio-emitting binary obtained by Lestrade et al. (1999) using very long baseline interferometry (VLBI). Their parallax of 43.93 ± 0.10 mas is about 10 times more precise than the *Hipparcos* catalog value of 46.11 ± 0.98 mas and 12 times more precise than the van Leeuwen (2007) measure of 47.35 ± 1.20 mas. The Lestrade et al. value is 2.2σ and 2.9σ lower than the *Hipparcos* and van Leeuwen measures, respectively. To check for systematic offsets, we compared the parallaxes for all overlapping stars in these three sources. While the difference in parallax is most significant for σ^2 CrB, we found no systematic differences. Moreover, Lestrade et al. performed statistical checks to verify the accuracy of their measure, so we adopt their parallax to derive the physical parameters of the component stars (Section 5).

[6] http://ad.usno.navy.mil/wds/

The Center for High Angular Resolution Astronomy (CHARA) Array's unique capabilities, facilitated by the world's longest optical interferometric baselines, have enabled a variety of astrophysical studies (e.g., McAlister et al. 2005; Baines et al. 2007; Monnier et al. 2007). This work utilizes the Array's longest baselines to resolve the 1.14-day spectroscopic binary, the shortest-period system yet resolved. While this is the first visual orbit determined using interferometric visibilities measured with the CHARA Array, the technique described here has regularly been employed for longer-period binaries using other long-baseline interferometers (e.g., Hummel et al. 1993; Boden et al. 1999). The σ^2 CrB binary has a projected angular separation of about 1.1 mas in the sky, making it easily resolvable for the CHARA Array, which has angular resolution capabilities in the K' band down to about 0.4 mas for binaries.

2. SPECTROSCOPIC MEASUREMENTS

Spectroscopic observations of σ^2 CrB were conducted at the Harvard-Smithsonian Center for Astrophysics (CfA) with an echelle spectrograph on the 1.5 m Wyeth reflector at the Oak Ridge Observatory in the town of Harvard, MA. A total of 46 usable spectra were gathered from 1992 May to 1999 July, each of which covers a single echelle order (45 Å) centered at 5188.5 Å and was recorded using an intensified photon-counting Reticon detector (see Latham 1992). The strongest lines in this window are those of the Mg I b triplet. The resolving power of these observations is $\lambda/\Delta\lambda \approx 35{,}000$, and the nominal signal-to-noise ratios (S/Ns) range from 21 to 94 per resolution element of 8.5 km s^{-1}.

Radial velocities were obtained using the two-dimensional cross-correlation algorithm TODCOR (Zucker & Mazeh 1994). Templates for the cross-correlations were selected from an extensive library of calculated spectra based on model atmospheres by R. L. Kurucz[7] (see also Nordström et al. 1994; Latham et al. 2002). These calculated spectra cover a wide range of effective temperatures ($T_{\rm eff}$), rotational velocities ($v \sin i$ when seen in projection), surface gravities ($\log g$), and metallicities. Experience has shown that radial velocities are largely insensitive to the surface gravity and metallicity adopted for the templates. Consequently, the optimum template for each star was determined from extensive grids of cross-correlations varying the temperature and rotational velocity, seeking to maximize the average correlation weighted by the strength of each exposure. The results we obtain, adopting $\log g = 4.5$ and solar metallicity[8] for both stars, are $T_{\rm eff} = 6050$ K and $v \sin i = 26$ km s^{-1} for the primary, and $T_{\rm eff} = 5870$ K and $v \sin i = 26$ km s^{-1} for the secondary. Estimated uncertainties are 150 K and 1 km s^{-1} for the temperatures and projected rotational velocities, respectively. Template parameters near these values were selected for deriving the radial velocities. The typical uncertainty for the velocities is 1 km s^{-1} for both stars.

The stability of the zero point of our velocity system was monitored by means of exposures of the dusk and dawn sky, and small run-to-run corrections were applied in the manner described by Latham (1992). Additional corrections for systematics were applied to the velocities as described by Latham et al. (1996) and Torres et al. (1997) to account for residual blending effects. These corrections are based on simulations with artificial composite spectra processed with TODCOR in the same way as the real spectra. The final heliocentric velocities and their 1σ errors are listed in Table 1, along with the corresponding epochs of observation, $O - C$ residuals, and orbital phase.

The light ratio between the components was estimated directly from the spectra following Zucker & Mazeh (1994). After corrections for systematics analogous to those described above, we obtain $\ell_{\rm s}/\ell_{\rm p} = 0.67 \pm 0.02$ at the mean wavelength of our observations (5188.5 Å). Given that the stars have slightly different temperatures, a small correction to the visual band was determined from synthetic spectra integrated over the V passband and the spectral window of our observations. The corrected value is $(\ell_{\rm s}/\ell_{\rm p})_V = 0.70 \pm 0.02$.

The visual companion σ^1 CrB was also observed spectroscopically at the CfA with the same instrumental setup. We obtained 18 observations between 1996 June and 2004 August. The stellar parameters were determined with a procedure similar to that used for σ^2 CrB, and yielded $T_{\rm eff} = 5950 \pm 100$ K and $v \sin i = 3 \pm 2$ km s^{-1}, for an adopted $\log g = 4.5$ and solar metallicity (see Footnote 8). Radial velocities were obtained with standard cross-correlation techniques using a template selected according to the above parameters. These measurements give an average velocity of -14.70 ± 0.11 km s^{-1}, with no significant variation within the observational errors. We use this radial velocity to unambiguously determine the longitude of the ascending node for the wider $\sigma^1-\sigma^2$ CrB visual orbit (Section 5.4).

2.1. Historical Data Sets

In addition to our own, four other radial-velocity data sets have been published in the literature (Harper 1925; Bakos 1984; Duquennoy & Mayor 1991; SR03). Except for the more recent one, the older data are generally of lower quality and contribute little to the mass determinations, but they do extend the time coverage considerably (to nearly 86 years, or 27,500 orbital cycles), and can be used to improve the orbital period. Because of our concerns over possible systematic differences among different data sets, particularly in the velocity semiamplitudes but also in the velocity zero points, we did not simply merge all these observations together indiscriminately, but instead we proceeded as follows. We considered all observations simultaneously in a single least-squares orbital fit, imposing a common period and epoch of maximum primary velocity in a circular orbit, but we allowed each data set to have its own velocity semiamplitudes ($K_{\rm p}$, $K_{\rm s}$) as well as its own systematic velocity zero-point offset relative to the reference frame defined by the CfA observations. Additionally, we included one more adjustable parameter per set to account for possible systematic differences between the primary and secondary velocities in each group. These were statistically significant only in the observations by SR03. Relative weights for each data set were determined by iterations from the rms residual of the fit, separately for the primary and secondary velocities. The resulting orbital period is $P = 1.139791423 \pm 0.000000080$ days, and the time of maximum primary velocity nearest to the average date of the CfA observations is $T = 2{,}450{,}127.61845 \pm 0.00020$ (HJD). We adopt this ephemeris for the remainder of the paper.

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7 Available at http://cfaku5.cfa.harvard.edu

8 SR03 have reported a metallicity for σ^2 CrB of [Fe/H] $= -0.37$ with an uncertainty no smaller than 0.1 dex, and Nordström et al. (2004) reported the value [Fe/H] $= -0.24$ based on Strömgren photometry. Metallicity determinations for double-lined spectroscopic binaries are particularly difficult, and both of these estimates are likely to be affected at some level by the double-lined nature of the system. However, the visual companion (σ^1 CrB) is apparently a single star, and has an accurate spectroscopic abundance determination by Valenti & Fischer (2005) giving [Fe/H] $= -0.06 \pm 0.03$, and another by Fuhrmann (2004) giving [Fe/H] $= -0.064 \pm 0.068$. The near-solar metallicity from these determinations is considered here to be more reliable.

Table 1
Radial Velocities of σ^2 CrB

HJD (2,400,000+)	RV_p (km s^{-1})	RV_s (km s^{-1})	σ_{RV_p} (km s^{-1})	σ_{RV_s} (km s^{-1})	$(O-C)_p$ (km s^{-1})	$(O-C)_s$ (km s^{-1})	Orbital Phase
48764.6474	6.88	−36.45	2.68	2.84	−1.72	−0.87	0.193
48781.6495	35.46	−64.08	2.99	3.16	1.15	−1.68	0.109
48810.6618	−69.00	46.22	1.16	1.23	0.47	0.37	0.564
48813.6236	18.25	−46.52	1.19	1.26	−0.89	0.06	0.162
48820.6185	−31.35	5.07	1.61	1.71	0.24	−1.27	0.299
48822.6494	41.46	−69.41	1.32	1.40	0.97	−0.55	0.081
48826.5581	−74.53	52.87	1.19	1.26	−0.38	2.13	0.510
48828.6849	−56.96	31.25	1.37	1.45	−0.33	−1.21	0.376
48838.5942	43.01	−71.62	1.15	1.22	0.62	−0.79	0.070
50258.6759	48.63	−75.42	1.43	1.51	0.73	1.17	0.984
50260.6371	−31.00	4.33	0.85	0.90	−0.66	−0.71	0.704
50263.6316	−42.68	17.76	0.83	0.88	0.40	−0.56	0.332
50266.6225	46.61	−73.03	0.99	1.04	0.74	1.43	0.956
50269.7633	−27.25	2.84	0.99	1.05	0.53	0.47	0.711
50271.6269	−46.41	23.01	0.95	1.01	1.46	−0.31	0.346
50275.6464	29.47	−57.26	0.97	1.03	−0.22	0.33	0.873
50285.6440	−49.95	26.91	0.90	0.95	0.84	0.54	0.644
50287.6352	−60.98	37.03	0.89	0.94	−0.45	0.51	0.391
50292.5697	−23.39	−1.49	1.02	1.08	0.90	−0.22	0.721
50295.6335	−65.17	39.49	0.79	0.83	−0.72	−1.13	0.409
50298.5502	46.99	−75.36	0.71	0.75	0.03	0.24	0.968
50300.5553	−22.15	−4.43	0.80	0.85	−0.21	−0.70	0.727
50302.6499	−69.55	44.72	0.84	0.89	−0.23	−0.98	0.565
50346.5051	46.86	−76.63	0.92	0.97	0.65	−1.81	0.041
50348.5107	4.35	−29.89	0.99	1.04	−1.77	3.10	0.801
50350.5649	−63.76	38.37	0.81	0.86	−1.83	0.39	0.603
50352.4779	−24.23	−1.41	0.79	0.84	0.74	−0.84	0.281
50356.4742	−0.04	−26.85	0.79	0.84	−1.27	1.05	0.787
50358.4740	−72.84	50.15	0.77	0.81	−0.68	1.49	0.542
50361.4826	13.31	−40.12	0.80	0.85	0.79	−0.45	0.182
50364.4624	1.84	−29.15	0.86	0.91	−2.54	2.04	0.796
50374.4574	−70.50	44.94	0.85	0.90	−1.26	−0.67	0.565
50379.4665	45.29	−73.75	0.82	0.87	−0.99	1.14	0.960
50383.4500	−70.47	48.43	0.84	0.89	1.34	0.13	0.455
50385.4760	−6.74	−19.80	0.81	0.86	−0.54	0.35	0.232
50388.4407	15.96	−44.52	0.92	0.97	−1.63	0.45	0.833
50391.4280	−71.44	49.52	0.81	0.86	0.32	1.28	0.454
50590.7488	−41.53	17.65	0.98	1.04	0.68	0.24	0.329
50619.6791	−26.78	3.14	1.05	1.11	1.06	0.72	0.711
50846.9255	39.45	−68.48	0.90	0.95	0.06	−0.78	0.087
51216.9001	−35.81	12.55	1.98	2.09	1.52	0.23	0.685
51246.7808	36.69	−66.52	2.01	2.13	−0.06	−1.57	0.901
51279.6859	−5.90	−19.52	2.51	2.65	−0.71	1.68	0.770
51341.7199	6.97	−33.48	1.77	1.87	−0.33	0.75	0.196
51374.6086	44.93	−73.34	2.01	2.12	−0.16	0.31	0.051
51374.6112	45.14	−74.26	3.08	3.26	0.34	−0.91	0.054

3. INTERFEROMETRIC MEASUREMENTS

Interferometric visibilities for σ^2 CrB were measured during 2007 May−July at the CHARA Array's six-element long-baseline interferometer located in Mount Wilson, CA (ten Brummelaar et al. 2005). The Array uses the visible wavelengths 480–800 nm for tracking and tip/tilt corrections, and the near-infrared K' (2.13 μm) and H (1.67 μm) bands for fringe detection. The 26 visibility measurements used in the final orbit determination, listed in Table 2, were obtained in the K' band on the S1–E1 and S1–E2 two-telescope baselines spanning projected baselines of 268–331 m. The interference fringes were obtained using the pupil-plane "CHARA Classic" beam combiner. While some of the data were obtained via on-site observing at Mount Wilson, the bulk of the data were gathered at the Arrington Remote Operations Center (AROC; Fallon et al. 2003) located on the Georgia State University campus in Atlanta, GA. Following the standard practice of time-bracketed observations, we interleaved each target visibility measurement with those of a calibrator star (HD 152598) in order to remove instrumental and atmospheric effects. For further details on the observing practice and the data reduction process, refer to McAlister et al. (2005).

We selected HR 6279 (HD 152598), an F0V star offset from σ^2 CrB by 8°.3, as the calibrator based on its small estimated angular diameter and its apparent lack of any close companions. We obtained photometric measurements for this star in the Johnson UBV bands from Grenier et al. (1985) and Perryman & ESA (1997), and JHK_S bands from the Two Micron All Sky Survey[9] (2MASS) and transformed them to calibrated

[9] http://www.ipac.caltech.edu/2mass

Table 2
Interferometric Visibilities for σ^2 CrB

HJD (2,400,000+)	Measured V	σ_V	Model V	$(O-C)_V$	u (m)	v (m)	Hour Angle (h)
54237.763	0.864	0.086	0.783	0.081	202.4	250.7	−2.24
54237.774	0.909	0.107	0.775	0.134	196.7	258.2	−1.99
54237.784	0.736	0.062	0.759	−0.022	190.3	265.2	−1.74
54237.796	0.702	0.063	0.729	−0.027	182.4	272.6	−1.46
54237.806	0.585	0.058	0.688	−0.103	174.6	278.9	−1.22
54237.816	0.652	0.076	0.625	0.027	165.6	285.3	−0.97
54237.833	0.468	0.053	0.474	−0.006	149.7	294.7	−0.56
54237.932	0.833	0.049	0.833	0.001	30.4	326.9	1.82
54237.942	0.775	0.059	0.791	−0.017	17.1	327.7	2.05
54237.954	0.672	0.038	0.672	0.001	0.5	328.1	2.34
54237.980	0.244	0.015	0.247	−0.004	−35.3	326.5	2.98
54247.701	0.858	0.113	0.887	−0.029	159.9	214.9	−3.08
54247.716	0.888	0.080	0.863	0.025	154.1	223.0	−2.73
54247.729	0.824	0.083	0.785	0.040	147.5	230.2	−2.40
54247.744	0.669	0.093	0.644	0.025	139.1	237.6	−2.05
54247.761	0.435	0.058	0.430	0.005	128.1	245.6	−1.64
54249.714	0.589	0.053	0.621	−0.032	152.1	225.3	−2.63
54249.726	0.570	0.054	0.609	−0.039	146.6	231.1	−2.36
54249.739	0.575	0.064	0.573	0.002	138.6	238.1	−2.03
54249.751	0.594	0.063	0.524	0.070	131.3	243.5	−1.75
54249.772	0.391	0.059	0.376	0.015	115.7	252.8	−1.24
54310.716	0.616	0.062	0.526	0.090	48.7	325.0	1.49
54310.726	0.405	0.050	0.410	−0.005	35.8	326.4	1.72
54310.776	0.477	0.050	0.454	0.023	−31.5	326.8	2.91
54310.786	0.558	0.054	0.619	−0.061	−45.5	325.4	3.16
54310.797	0.870	0.100	0.745	0.125	−59.5	323.5	3.42

flux measurements using the methods described in Colina et al. (1996) and Cohen et al. (2003). We then fitted these fluxes to spectral energy distribution models,[10] yielding an angular diameter of 0.467 ± 0.013 mas for HD 152598, corresponding to $T_{\rm eff} = 7150$ K and $\log g = 4.3$. This diameter estimate results in a predicted calibrator visibility of $V_{\rm cal} = 0.858 \pm 0.008$ at our longest baseline of 330 m, contributing roughly 1% error to the calibrated visibilities. This error is included in our roughly 10% total visibility errors listed in Table 2, along with the epoch of observation (at mid-exposure), the target star's calibrated visibility, the predicted visibility for the best-fit orbit, the $O-C$ visibility residual, the baseline projections along the east–west (u) and north–south (v) directions, and the hour angle of the target.

4. DETERMINATION OF THE ORBIT

Consistent with prior evidence of a synchronized orbit (SR03), we adopt a circular orbit ($e \equiv 0$, $\omega \equiv 0$) with the orbital period (P) and epoch of nodal passage (T) from Section 2.1 for the spectroscopic and visual orbit solutions presented below.

4.1. Spectroscopic Orbital Solutions

Our measured radial velocities enable us to derive the three remaining spectroscopic orbital elements, namely, the center-of-mass velocity (γ) and the radial velocity semi-amplitudes of the primary and secondary ($K_{\rm p}$ and $K_{\rm s}$, respectively). To check for consistency with prior efforts, we used the velocities published in SR03 to derive a second orbital solution. The calculated radial velocities for the derived orbits are shown in Figures 1 and 2 (the solid and dashed curves for the primary and secondary, respectively) along with the measured radial velocities and residuals for the primary (filled circles) and secondary (open circles). The corresponding orbital solutions are presented in Table 3 along with the related derived quantities. For comparison purposes, we have also included the values presented in SR03, which are consistent with our orbit generated using their velocities. However, the orbit obtained using our velocities is statistically different from that obtained using SR03 velocities. While the primary's velocity semi-amplitude matches within the errors between these two solutions, the secondary's differs by over 5σ, resulting in a 4σ difference in the mass ratios.

One possible explanation of the difference in the orbital solutions could be the velocity residuals for the orbit using SR03 data (Figure 2), which show an obvious pattern for both components. Those observations were obtained on four nights over a five-day period. To further examine these patterns, we display the residuals for each of the four nights in Figure 3, as a function of time. Clear trends are seen on each night, which are different for the primary and secondary components and have peak-to-peak excursions reaching 4 km s^{-1} in some cases, significantly larger than the velocity errors of 0.1–1.2 km s^{-1} (SR03). On some, but not all, nights there appears to be a periodicity of roughly 0.20–0.25 days. The nature of these trends is unclear, particularly because this periodicity is much shorter than either the orbital or the rotational periods. Instrumental effects seem unlikely, but an explanation in terms of the considerable spottedness of both stars is certainly a distinct possibility. The Doppler imaging maps produced by SR03 show that both components display a very patchy distribution of surface features covering the polar regions. Individual features coming in and out of view as the stars rotate could easily be the cause of the systematic effects observed in the radial velocities, and the effects would not necessarily have to be the same on both stars, just as observed. Slight changes in the spots from one night to the next could account for the different patterns

[10] The model fluxes were interpolated from the grid of models from R. L. Kurucz, available at http://cfaku5.cfa.harvard.edu

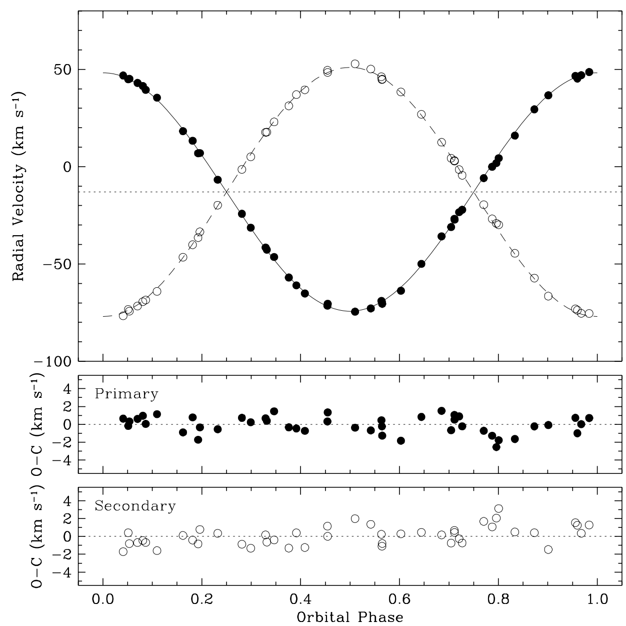

Figure 1. Our radial velocities and the orbital fit for σ^2 CrB (top panel) and the primary and secondary residuals (bottom panels). The filled circles represent the primary and the open circles represent the secondary component. The corresponding orbital elements are listed in Table 3.

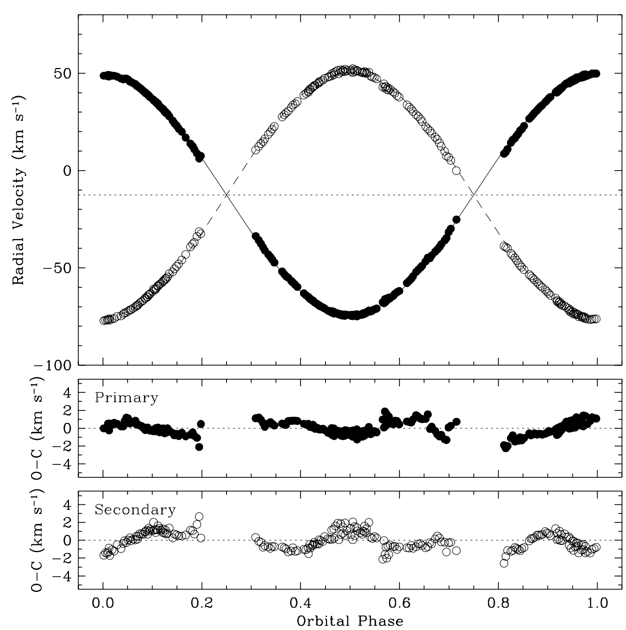

Figure 2. Same as Figure 1, but based on SR03 radial velocities.

Table 3
Spectroscopic Orbital Solutions for σ^2 CrB

Element	This Work	SR03 Velocities[a]	SR03 Results
Orbital elements			
P (days)	1.139791423 ± 0.000000080[b]	1.139791423 ± 0.000000080[b]	1.1397912 (adopted)
T (HJD-2,400,000)[c]	50, 127.61845 ± 0.00020[b]	50, 127.61845 ± 0.00020[b]	50,127.6248[d]
e	0.0[e]	0.0[e]	0.0[e]
ω (deg)	0.0[e]	0.0[e]	0.0[e]
γ (km s^{-1})	−13.03 ± 0.11	−12.58 ± 0.05	−12.3 ± 0.06
K_p (km s^{-1})	61.25 ± 0.21	61.31 ± 0.06	61.34 ± 0.06
K_s (km s^{-1})	63.89 ± 0.22	62.90 ± 0.08	62.91 ± 0.08
Derived quantities			
$M_p \sin^3 i$ ($M_\odot$)	0.11818 ± 0.00092	0.11461 ± 0.00032	0.1147
$M_s \sin^3 i$ ($M_\odot$)	0.11329 ± 0.00086	0.11170 ± 0.00027	0.1118
$q \equiv M_s/M_p$	0.9586 ± 0.0047	0.9746 ± 0.0016	0.975 ± 0.002
$a_p \sin i$ (10^6 km)	0.9600 ± 0.0033	0.96085 ± 0.00097	0.96138 ± 0.00093
$a_s \sin i$ (10^6 km)	1.0014 ± 0.0035	0.98592 ± 0.00126	0.9861 ± 0.0012
$a \sin i$ ($R_\odot$)	2.8181 ± 0.0068	2.7971 ± 0.0023	2.798 ± 0.002
Other quantities pertaining to the fit			
N_{obs}	46	217	217
Time span (days)	2610	5.4	5.4
σ_p (km s^{-1})[f]	1.04	0.74	0.71
σ_s (km s^{-1})[f]	1.10	0.97	...

Notes.
[a] Our orbital solution using SR03 velocities.
[b] Determined using all published velocities (see Section 2.1).
[c] T is the epoch of maximum primary velocity.
[d] The value from SR03 has been shifted by an integer number of cycles to the epoch derived in this work, for comparison purposes.
[e] Circular orbit adopted.
[f] RMS residual from the fit.

seen in Figure 3. The relatively large amplitude of the residual variations raises the concern that they may be affecting the velocity semi-amplitudes of the orbit, depending on the phase at which they occur. We do not see such trends in the CfA data, perhaps because our observations span a much longer time (more than 7 years, and ∼2200 rotational cycles), allowing for spots to change and average out these effects. We therefore proceed on the assumption that possible systematic effects of this nature on K_p and K_s are lessened in the CfA data.

4.2 The Visual Orbit Solution

The basic measured quantity from an interferometric observation is *visibility*, which evaluates the contrast in the fringe pattern obtained by combining starlight wave fronts from multiple apertures, filtered through a finite bandwidth. For a single star of angular diameter θ, the interferometric visibility V for a uniform disk model is given by

$$V = \frac{2J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}, \quad (1)$$

where J_1 is the first-order Bessel function, B is the projected baseline length as seen by the star, and λ is the observed bandpass central wavelength. The interferometric visibility for a binary, where the individual stars have visibilities V_p (primary) and V_s (secondary) per Equation (1), is given by

$$V = \frac{\sqrt{\left(\beta^2 V_p^2 + V_s^2 + 2\beta V_p V_s \cos((2\pi/\lambda)\mathbf{B}\cdot\mathbf{s})\right)}}{1+\beta}, \quad (2)$$

where β is the primary to secondary flux ratio, $\mathbf{B}$ is the projected baseline vector as seen by the binary, and $\mathbf{s}$ is the binary's angular-separation vector in the plane of the sky.

Using our measured interferometric visibilities and the above equations, we are able to augment the spectroscopic orbital solutions to derive a visual orbit for σ^2 CrB. Adopting the period and epoch of nodal passage from Section 2.1, we now derive the parameters that can only be determined astrometrically: angular semimajor axis (α), inclination (i), and longitude of the ascending node (Ω). We also treat the K'-band magnitude difference as a free parameter in order to test evolutionary models.

For a circular orbit, the epoch of periastron passage (T_0) is replaced by the epoch of ascending nodal passage (T_{node}), defined as the epoch of fastest secondary recession, in the visual orbit equations (Heintz 1978). Accordingly, we translate the T value listed in Section 2.1 by one-half of the orbital period to determine the epoch of the ascending nodal passage as $T_{node} = 2{,}450{,}127.04855 \pm 0.00020$ (HJD) for use in our visual orbit solution. The 1σ errors of this and other adopted parameters listed in Table 4 have been propagated to our error estimates for the derived parameters.

The angular diameters of the components are too small to be resolved by our K'-band observations. We therefore estimate these based on the components' absolute magnitudes and temperatures as described below. We first estimate the Johnson V-band magnitude of σ^2 CrB using its *Tycho*-2 magnitudes of $B_T = 6.262 \pm 0.014$ and $V_T = 5.620 \pm 0.009$ and the relation $V_J = V_T - 0.090(B_T - V_T)$ from the Guide to the *Tycho*-2 Catalog. Then, using the V-band flux ratio from Section 2 and the Lestrade et al. (1999) parallax, we obtain absolute magnitudes of $M_V = 4.35 \pm 0.02$ for the primary and $M_V = 4.74 \pm 0.02$ for the secondary. These magnitudes lead to linear radius estimates of 1.2 $R_\odot$ for the primary and 1.1 $R_\odot$ for the secondary using the tabulation of stellar physical parameters in Popper (1980) and

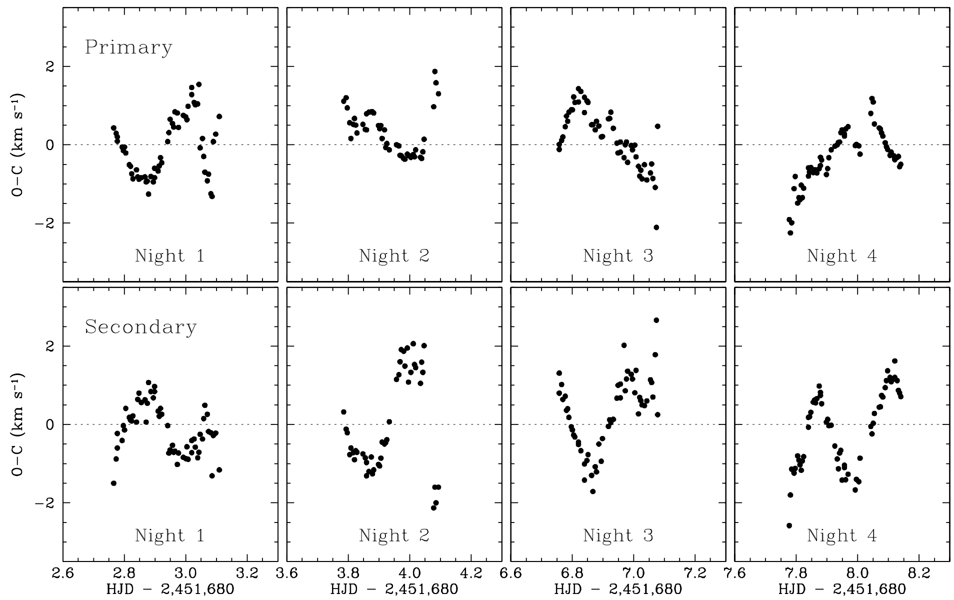

Figure 3. Residuals for the individual nights' velocities from SR03.

Andersen (1991). Finally, using the Lestrade et al. (1999) parallax, we adopt component angular diameters of $\theta_p = 0.50$ mas and $\theta_s = 0.45$ mas, propagating a 0.05 mas uncertainty in these values for deriving the uncertainty of our orbital elements. Diameter estimates using the temperatures of the components from Section 2 are consistent with these values.

We conduct an exhaustive search of the parameter space for the unknown parameters mentioned, namely, α, i, Ω, and $\Delta K'$. The orbital inclination is constrained by the $a \sin i$ from spectroscopy, the free-parameter α, and the Lestrade et al. (1999) parallax. We impose this constraint during our exploration of the parameter space along with its associated 1σ error. We explore the unknown parameters over many iterations, by randomly selecting them between broad limits and using Equation (2) to evaluate the predicted binary visibility for the baseline and binary positions at each observational epoch. The orbital solution presented here represents the parameter set with the minimum χ^2 value when comparing the predicted and measured visibilities.

Figure 4 shows the measured visibilities (plus signs) with vertical error bars for each of the 26 observations, along with the computed model visibilities (diamonds), and Table 2 lists the corresponding numerical values of the observed and model visibilities along with the residuals of the fit. Table 4 summarizes the visual orbit parameters for σ^2 CrB from our solution and Figure 5 plots the visual orbit in the plane of the sky. As seen in Figure 5, we have a reasonably good phase coverage from our observations.

As mentioned in Section 4.1, star spots can create systematic effects in the data obtained on this binary. These effects are especially significant for data obtained over a short time baseline, as seen for the SR03 spectroscopic solution. While our interferometric data span 73 days, allowing for some averaging of these effects, the bulk of the data used were obtained over 12 days, justifying an exploration of this effect. Specifically, the separation between the stars derived from our visibility data would represent the separation of the centers of light rather than that of mass. As discussed in Hummel et al. (1994), heavily spotted stars will incur a systematic shift in the center

Table 4
Visual Orbit Solution for σ^2 CrB

Orbital Parameter	Value
Adopted values	
Period (days)	1.139791423 ± 0.000000080[a]
T_{node} (HJD-2,400,000)[b]	50, 127.04855 ± 0.00020
e	0.0[c]
ω (deg)	0.0[c]
θ_p (mas)	0.50 ± 0.05[d]
θ_s (mas)	0.45 ± 0.05[d]
Visual orbit parameters	
α (mas)	1.225 ± 0.013
i (deg)	28.08 ± 0.34
Ω (deg)	207.93 ± 0.67[e]
$\Delta K'$	0.19 ± 0.19
Reduced χ^2	0.61[f]

Notes.
[a] See Section 2.1.
[b] This is the epoch of the ascending node, defined as the epoch of maximum secondary velocity, and accordingly is one-half period less than the value in Table 3 (see Section 4.2).
[c] Circular orbit adopted.
[d] See Section 4.2.
[e] This value suffers from a 180°ambiguity due to the cosine term in Equation (2).
[f] The low χ^2 indicates that our error estimates for visibility are conservative.

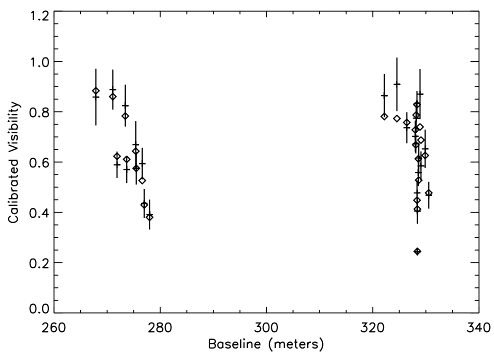

Figure 4. Calibrated visibility measurements for σ^2 CrB vs. the projected baseline. The plus signs are the calibrated visibilities with vertical error bars, and the diamonds are the calculated visibilities for the best-fit orbit. Table 2 lists the numeric values corresponding to this plot.

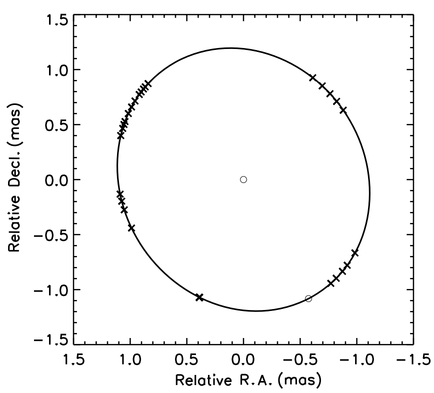

Figure 5. Visual orbit of σ^2 CrB. The open circles mark the positions of the two components at the epoch of ascending nodal passage, and the X marks identify the secondary's calculated positions at the epochs of visibility measurement.

of light from rotational and orbital motions, perhaps inducing an additional uncertainty in the orbital elements derived. We assume a spot-induced change in the angular semimajor axis of 2% of the primary's diameter, or 0.01 mas. This is less than the uncertainty of our derived semimajor axis, and at our baselines of 270–330 m translates to a 0.005–0.011 change in the visibility. While the uncertainties of our measured visibilities are an order of magnitude larger than this, we ran a test orbital fit by adding a 0.010 uncertainty to the visibility errors as a root-sum-squared. While, as expected, the χ^2 of the fit improved, the values and uncertainties of the derived parameters remained unchanged, leading us to conclude that this effect, while real, is too small to affect our results.

We determine the 1, 2, and 3σ uncertainties of each visual orbit parameter using a Monte Carlo simulation approach. We compute the orbital fit for 100,000 iterations, where for each iteration, we randomly select the adopted parameters within their respective 1σ intervals and the model parameters around their corresponding best-fit solution, generating a multi-dimensional χ^2 "surface." Then, we project this surface along

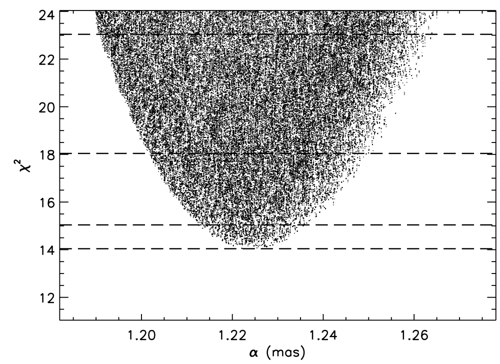

Figure 6. χ^2 distribution around the best-fit solution for the angular semimajor axis (α). The bottom dashed line corresponds to the minimum χ^2 value, and the others mark a deviation of 1, 4, and 9 units above the minimum, corresponding to 1, 2, and 3-σ errors.

each parameter axis, resulting in the plots shown in Figures 6–9. The figures show the χ^2 distribution around the best-fit orbit and enable estimation of 1, 2, and 3σ errors for each parameter based on a χ^2 deviation of 1, 4, and 9 units, respectively, from its minimum value. The horizontal dashed lines in the figures from bottom to top mark the minimum χ^2 value and those corresponding to 1, 2, and 3σ errors, and Table 4 lists the corresponding numerical 1σ errors of the model parameters.

5. PHYSICAL PARAMETERS

5.1. Component Mass Estimates

Our angular semimajor axis obtained from interferometry translates to 0.0279 ± 0.0003 AU or 5.99 ± 0.07 $R_\odot$ using the Lestrade et al. (1999) parallax. Newton's generalization of Kepler's third law then yields a mass sum of 2.227 ± 0.073 $M_\odot$ for the pair, and using the mass ratio from our spectroscopic solution of 0.9586 ± 0.0047, we get individual component masses of 1.137 ± 0.037 $M_\odot$ and 1.090 ± 0.036 $M_\odot$ for the primary and secondary, respectively. As noted in Section 4.1, the SR03 velocities yield a significantly different mass ratio of 0.9746 ± 0.0016, but this 4σ difference is not enough to influence the mass estimates significantly. The uncertainty in our masses is dominated by the cubed semimajor axis factor in estimating the mass sum, resulting in about a 3% uncertainty in mass sum corresponding to a 1% uncertainty in the semimajor axis. The high precision of the mass ratio from the spectroscopic solution results in final masses of 3% uncertainty as well. Component mass estimates using the SR03 velocities are 1.128 ± 0.037 and 1.099 ± 0.036, in excellent agreement with the masses using our velocities. These masses along with other physical parameters derived are listed in Table 5.

5.2. Radii of the Components

Assuming synchronous and co-aligned rotation of spherical components, reasonable given the short orbital period and evidence from SR03 of unevolved stars contained within their Roche limits, we can estimate the component radii from the measured spectroscopic $v \sin i$. As mentioned in Section 2, our spectra yield $v \sin i = 26 \pm 1$ km s^{-1} for both the primary and secondary. These values and uncertainties are identical to

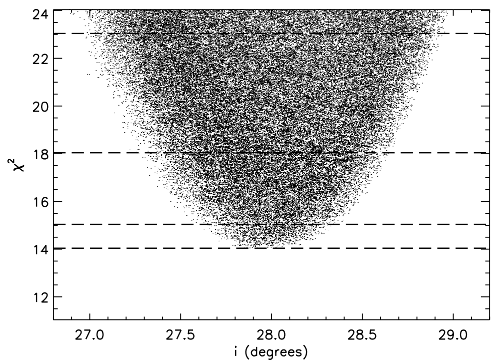

Figure 7. Same as Figure 6, but for the orbital inclination (i).

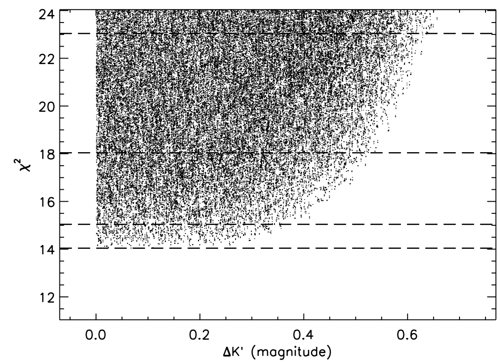

Figure 9. Same as Figure 6, but for the K'-band magnitude difference ($\Delta K'$).

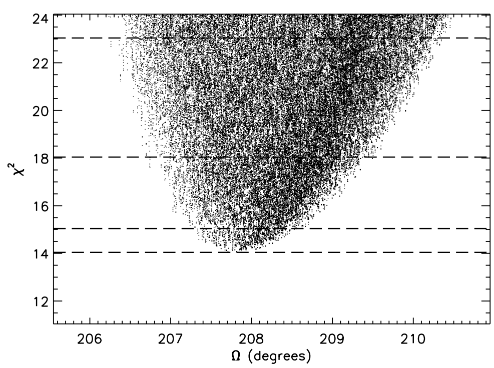

Figure 8. Same as Figure 6, but for the longitude of the ascending node (Ω).

those in SR03. Using the inclination from our visual orbit, and adopting the orbital period from spectroscopy as the rotational period, we get identical component radii of $1.244 \pm 0.050\ R_\odot$ for the primary and secondary. This translates to an angular diameter of 0.509 ± 0.020 mas for each component using the Lestrade et al. (1999) parallax, in excellent agreement with our adopted diameter for the primary and a 1σ variance for the secondary, given our associated 0.05 mas errors for these values. These radii estimates, along with the effective temperatures from Section 2 and the relation $L \propto R^2 T_{\rm eff}^4$, lead to a luminosity ratio of 0.89 ± 0.16. Alternatively, using bolometric corrections from Flower (1996) of $BC_p = -0.038 \pm 0.017$ and $BC_s = -0.064 \pm 0.020$ corresponding to the components' effective temperatures, the V-band flux ratio of 0.70 ± 0.02 from spectroscopy translates to a total luminosity ratio of 0.68 ± 0.20, a 1σ variance from the estimate above. Conversely, our estimates of effective temperature and luminosity ratio require a radius ratio of 0.88 ± 0.14, again at a 1σ variance from the 1.00 ± 0.06 estimate from the identical $v \sin i$ values of the components.

5.3. Absolute Magnitudes and Ages

We allowed the K'-band magnitude difference to be a free parameter for our visual orbit fit, obtaining $\Delta K' = 0.19 \pm 0.19$, consistent with the 0.18 estimate from the mass–luminosity relations of Henry & McCarthy (1993).[11] The uncertainty in $\Delta K'$ is large because visibility measurements of nearly equal mass, and hence nearly equal brightness, pairs are relatively insensitive to the magnitude difference of the components (Hummel et al. 1998; Boden et al. 1999). Using Equation (2), we have verified that a 10% change in $\Delta K'$ for σ^2 CrB results in only 0.1% change in visibility. This, along with the poor-quality K magnitude listed in 2MASS (for σ^2 CrB, $K = 4.052 \pm 0.036$, but flagged as a very poor fit), thwart any attempts to use these magnitudes for

[11] The relations from Henry & McCarthy are for $0.5\ M_\odot \leqslant$ Mass $\leqslant 1.0\ M_\odot$. We consider it safe to extrapolate out to our estimated masses of slightly larger than $1.0\ M_\odot$.

Table 5
Physical Parameters for σ^2 CrB

Physical Parameter	This Work		SR03 Spectroscopy[a]		SR03 Results	
	Primary	Secondary	Primary	Secondary	Primary	Secondary
a ($R_\odot$)	5.99 ± 0.07		5.99 ± 0.07		...	
Mass ($M_\odot$)	1.137 ± 0.037	1.090 ± 0.036	1.128 ± 0.037	1.099 ± 0.036	1.108 ± 0.004[b]	1.080 ± 0.004[b]
Radius ($R_\odot$)	1.244 ± 0.050	1.244 ± 0.050	1.244 ± 0.050	1.244 ± 0.050	1.14 ± 0.04	1.14 ± 0.04
$T_{\rm eff}$ (K)	6050 ± 150	5870 ± 150	6000 ± 50	5900 ± 50	6000 ± 50	5900 ± 50
$M_{\rm V}$ (mag)	4.35 ± 0.02	4.74 ± 0.02	4.45 ± 0.02	4.61 ± 0.02	4.61 ± 0.07	4.76 ± 0.07
$M_{\rm K}$ (mag)	2.93 ± 0.09	3.12 ± 0.11	...	...	...	...

Notes.
[a] These parameters use the SR03 spectroscopic results such as flux ratio, rotational velocities, and radial velocities, but use the Lestrade et al. (1999) parallax, *Tycho*-2 magnitudes, and our visual orbit.
[b] As noted in Section 1, these uncertainties are unrealistically small.

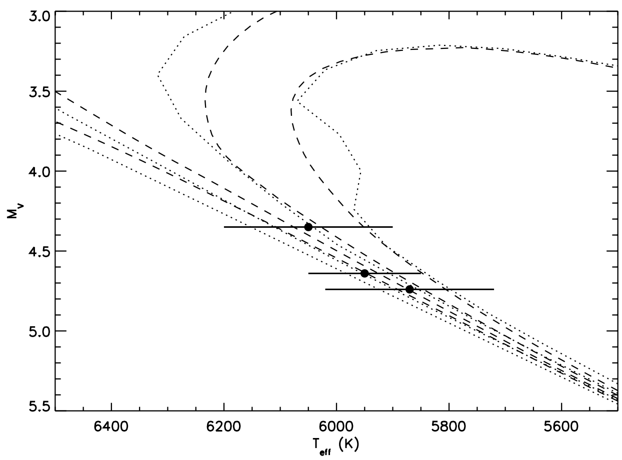

Figure 10. Position of the Sun-like components of σ CrB on the H–R diagram. The points from top to bottom are σ^2 CrB primary, σ^1 CrB, and σ^2 CrB secondary. The isochrones are from the Yonsei–Yale (dotted) and Victoria–Regina (dashed models) for 0.5, 1.5, 3.0, and 5.0 Gyr ages (left to right) for solar metallicity stars.

checking stellar evolution models. However, we can revert to *V*-band photometry to explore this topic.

In Section 4.2, we derived the absolute *V*-band magnitudes of the components of σ^2 CrB as $M_V = 4.35 \pm 0.02$ for the primary and $M_V = 4.74 \pm 0.02$ for the secondary. For σ^1 CrB, we similarly use the *Tycho*-2 magnitudes and the Lestrade et al. (1999) parallax to obtain $M_V = 4.64 \pm 0.01$. SR03 had a smaller magnitude difference for the components of σ^2 CrB, and the corresponding results using their spectroscopy are also included in Table 5 along with the values from their paper. Figure 10 plots these three stars on a Hertzsprung–Russell (H–R) diagram using our magnitude and temperature estimates, along with isochrones for 0.5, 1.5, 3.0, and 5.0 Gyr ages (left to right) from the Yonsei–Yale isochrones (dotted, Yi et al. 2001) and the Victoria–Regina stellar evolution models (dashed, VandenBerg et al. 2006) for solar metallicity (see Footnote 8).

Wright et al. (2004) estimate an age of 1.8 Gyr for σ^1 CrB based on chromospheric activity, and Valenti & Fischer (2005) estimate an age of 5.0 Gyr from spectroscopy with limits of 2.9–7.8 Gyr based on 1σ changes to $\log L$. SR03 identify a much lower age, of a few times 10^7 years, by matching pre-main-sequence evolutionary tracks and point to their higher Li abundance as supporting evidence. While abundance determinations in double-lined spectroscopic binaries are particularly difficult and more prone to errors, the high-Li abundance of 2.60 ± 0.03 (SR03) for the slow-rotating single-lined companion σ^1 CrB does argue for a young system. Each point along the isochrones plotted in Figure 10 corresponds to a particular mass, allowing us to use our mass estimates for the components of σ^2 CrB to further constrain the system's age. Our mass, luminosity, and temperature estimates indicate an age for this system of 0.5–1.5 Gyr, with a range of 0.1–3 Gyr permissible within 1σ errors.

5.4. Mass Estimate of σ^1 CrB

Our mass estimates for the components of σ^2 CrB allow us to constrain the mass of the wider visual companion σ^1 CrB as well. Scardia (1979) presented an improved visual orbit for the AB pair based on 886 observations spanning almost 200 years of observation, yielding $P = 889$ years, $a = 5\farcs9$, $i = 31\fdg8$, $e = 0.76$, and $\Omega = 16\fdg9$. However, he did not publish uncertainties for these parameters, and given the long period, his less than one-third phase coverage leads to only a preliminary orbital solution, albeit one that convincingly shows orbital motion of the pair. He further uses parallaxes available to him to derive a mass sum for the AB system of 3.2 $M_\odot$. We used all current WDS observations, adding almost 200 observations since Scardia (1979), to update this orbit and obtain uncertainties for the parameters. Our visual orbit is presented in Figure 11, along with the Scardia orbit for comparison, and Table 6 lists the derived orbital elements. Adopting the Lestrade et al. (1999) parallax of the A component, we estimate a mass sum of 3.2 ± 0.9 $M_\odot$, resulting in a B-component mass estimate of 1.0 $M_\odot$, consistent with its spectral type of G1 V (Gray et al. 2003). Valenti & Fischer (2005) estimate a mass of 0.77 ± 0.21 $M_\odot$ based on high-resolution spectroscopy, but we believe that they systematically underestimate their uncertainty by overlooking the $\log e$ factor in converting from uncertainty in $\log L$ to uncertainty in L. Using the $\log e$ factor, we followed their methods for obtaining a mass estimate of 0.77 ± 0.44 $M_\odot$. The mass error is dominated by the uncertainty of the Gliese & Jahreiß (1991) parallax used by Valenti & Fischer (2005). Adopting the higher precision Lestrade et al. (1999) parallax of the primary, we follow their method, and using the $\log e$ factor, get a mass estimate of 0.78 ± 0.11 $M_\odot$. This mass is too low for the spectral type (as well as our own estimate of the effective temperature; see Section 2) and the expectation from the visual orbit.

Table 6
Visual Orbit Solution for σ^1–σ^2 CrB

Orbital Parameter	Value
P (years)	726 ± 62
T_0 (BY)	1825.2 ± 1.5
e	0.72 ± 0.01
ω (deg)	237.3 ± 6.8
α (arcsec)	5.26 ± 0.35
i (deg)	32.3 ± 4.1
Ω (deg)	28.0 ± 0.5

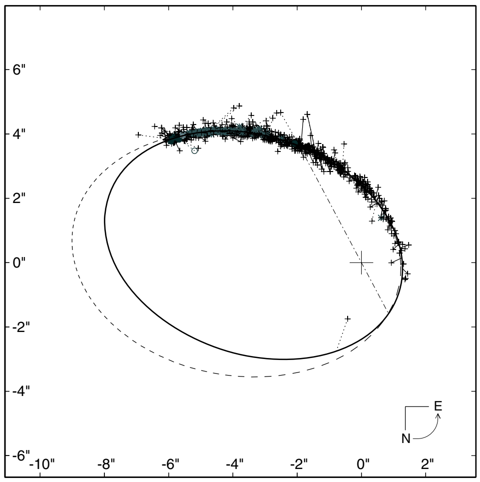

Figure 11. Visual orbit of the wider $\sigma^1 - \sigma^2$ CrB (AB) system based on all measures in the WDS. The plus signs indicate micrometric observations, the asterisks indicate photographic measures, open circles indicate eyepiece interferometry, and the filled circles represent speckle interferometry. The solid curve is our orbit fit and the dashed curve is the Scardia (1979) orbit. $O - C$ lines connect each measure to its predicted position along the orbit. The big plus at the origin indicates the position of the primary and the dot-dashed line through it is the line of nodes. Scales are in arcseconds, and the curved arrow at the lower right corner by the north and east direction indicators shows the direction of orbital motion.

A possible contamination of the secondary's spectral type from the 7″ distant primary is unlikely, as determined by Richard Gray at our request from new spectroscopic observations (R. Gray 2008, private communication).

The inclination and longitude of the ascending node for this visual orbit are similar to those of the inner (σ^2 CrB) orbit, suggesting coplanarity. For the outer visual orbit, we can use our radial velocity estimate for σ^1 CrB, our derived systemic velocity for σ^2 CrB, and the speckle observations to unambiguously determine the longitude of the ascending node as $\Omega = 28.^\circ0 \pm 0.^\circ5$. Using the equation for the relative inclination of the two orbits (ϕ) from Fekel (1981), we get $\phi = 4.^\circ7$ or $60.^\circ3$, given the 180°ambiguity in Ω for the inner orbit, confirming coplanarity as a possibility.

6. THE WIDE COMPONENTS: OPTICAL OR PHYSICAL?

In addition to the three solar-type stars, the WDS lists three additional components for σ CrB. We present evidence to show that WDS components C and D are optical alignments, while component E, itself a binary, is a physical association. WDS component C (ADS 9979C), measured 18″ away at 103° in 1984 (Popović 1986), has a proper motion of $\mu_\alpha = -0.''016$ yr^{-1} and $\mu_\delta = -0.''015$ yr^{-1} (Jeffers et al. 1963), significantly different from that of σ^2 CrB of $\mu_\alpha = -0.''26364 \pm 0.''00091$ yr^{-1} and $\mu_\delta = -0.''09259 \pm 0.''00129$ yr^{-1} from van Leeuwen (2007). Similarly, component D, measured 88″ away at 82° in 1996 (Courtot 1996) and clearly seen by us as a field star by blinking the multi-epoch STScI Digitized Sky Survey[12] (DSS) images, has a proper motion of $\mu_\alpha = +0.''004$ yr^{-1} and $\mu_\delta = -0.''017$ yr^{-1} (Jeffers et al. 1963), again significantly different from that of σ^2 CrB. As a confirmation of the optical alignment, we compare in Figures 12 and 13 the observed separations of components C and D, respectively, from the primary with the corresponding expected values based

[12] http://stdatu.stsci.edu/cgi-bin/dss_form

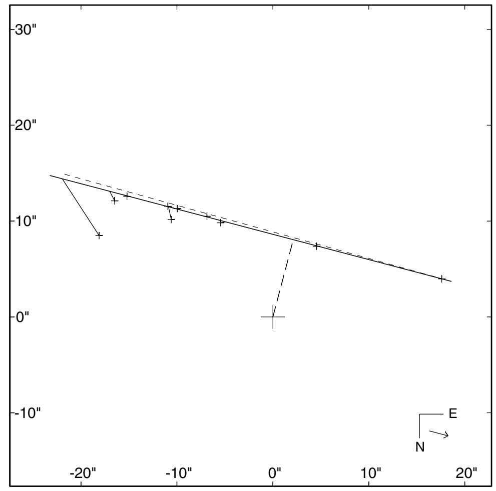

Figure 12. Relative separation between σ^2 CrB and ADS 9979C based on 10 resolutions of the pair from 1832 to 1984. The plus signs indicate micrometric observations. The $O - C$ lines connect each measure to its predicted position along the linear fit (thick solid line). The thick dashed line is the predicted movement based on the differential proper motions. The long dashed line connected to the origin indicates the predicted closest apparent position. The scale is in seconds of arc. An arrow in the lower right corner by the north and east direction indicators shows the direction of motion of the star.

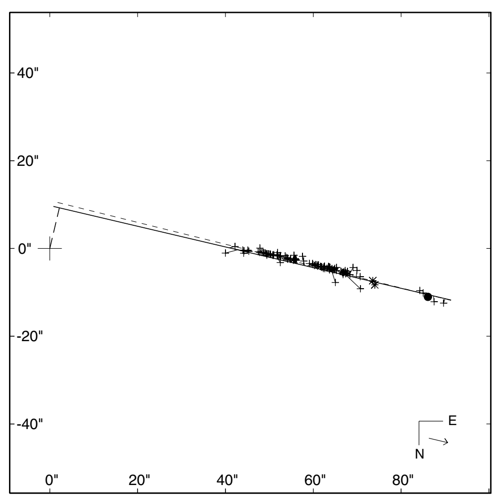

Figure 13. Same as Figure 12, but for ADS 9979D based on 106 resolutions of the pair from 1825 to 1996. The asterisks indicate photographic measures and the filled circles represent *Tycho* measures.

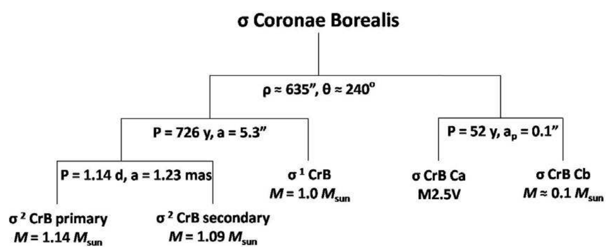

Figure 14. Mobile diagram of σ CrB and some of its properties. The Ca–Cb pair is WDS component E, while WDS components C & D are not gravitationally bound to the σ CrB system (see Figures 12 and 13, and the text in Section 6). a_p for the Ca–Cb pair is the photocentric semimajor axis.

on their proper motions. The solid line is a linear fit to the published measurements from the WDS and the dashed line is the expected separation based on differential proper motion. The excellent agreement between the two lines for both components confirms them as field stars.

WDS component E (σ CrB C, HIP 79551) is widely separated from the primary at 635″, translating to a minimum physical separation of over 14,000 AU using the Lestrade et al. (1999) parallax. Despite its wide separation, this component appears to be physically associated with σ CrB based on its matching parallax of $\pi = 45.40 \pm 3.71$ mas and proper motion of $\mu_\alpha = -0\farcs26592 \pm 0\farcs00299$ yr^{-1} and $\mu_\delta = -0\farcs08363 \pm 0\farcs00368$ yr^{-1} (van Leeuwen 2007). While seemingly extreme for gravitationally bound systems, physical association has been demonstrated for pairs with separations out to 20,000 AU (e.g., Latham et al. 1991; Poveda et al. 1994). σ CrB C has a spectral classification of M2.5V (Reid et al. 1995), apparent magnitude of $V = 12.24$ (Bidelman 1985), and has itself been identified as a photocentric motion binary with an unseen companion of 0.1 $M_\odot$ in a 52 year orbit (Heintz 1990). Perryman & ESA (1997) also identify this star as a binary of type "X" or stochastic solution, implying a photocenter wobble for an unresolved star, but for which the *Hipparcos* data are not sufficient to derive an orbit.

7. CONCLUSION

Augmenting our radial velocity measurements with published values, we obtain a coverage of nearly 86 years or 27,500 orbital cycles, resulting in a very precise ephemeris of $P = 1.139791423 \pm 0.000000080$ days and $T = 2{,}450{,}127.61845 \pm 0.00020$ (HJD) and a robust spectroscopic orbit for σ^2 CrB. Using the CHARA Array, we have resolved this 1.14 day spectroscopic binary, the shortest-period system yet resolved, and derived its visual orbit. The resulting component masses are $1.137 \pm 0.037\ M_\odot$ and $1.090 \pm 0.036\ M_\odot$ for the primary and secondary, respectively. Our spectroscopy supports prior efforts in estimating the same $v \sin i$ values for both components, which assuming a synchronized, co-aligned rotation results in equal radii of $1.244 \pm 0.050\ R_\odot$ for both components. The corresponding radius ratio is consistent within 1σ with its estimate using the components' temperatures and flux ratio from spectroscopy. We have also shown that this binary resides in a hierarchical quintuple system, composed of three close Sun-like stars and a wide M-dwarf binary. The wider visual orbit companion, σ^1 CrB, is about 7″ away in a 726-year visual orbit with $i = 32\fdg3$, which appears to be coplanar with the inner orbit. A comparison of the mass and absolute magnitude estimates of σ^1 CrB and σ^2 CrB with current stellar evolution models indicates a young age for the system of 0.1–3 Gyr, consistent with the relatively high Li abundance previously measured. Finally, the widest member of this system is an M-dwarf binary, σ CrB C, at a minimum separation of 14,000 AU. Figure 14 depicts the system's hierarchy in a pictorial form.

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