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SEARCH FOR FAINT COMPANIONS TO NEARBY SOLAR-LIKE STARS USING THE ADAPTIVE OPTICS SYSTEM AT MOUNT WILSON OBSERVATORY[1]

Nils H. Turner
Mount Wilson Institute, P.O. Box 48, Mount Wilson, CA 91023; and Center for High Angular Resolution Astronomy, Georgia State University; nils@mtwilson.edu

Theo A. ten Brummelaar and Harold A. McAlister
Center for High Angular Resolution Astronomy, Georgia State University, Mount Wison, CA 91023; theo@mtwilson.edu, hal@chara.gsu.edu

Brian D. Mason[2] and William I. Hartkopf[2]
United States Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC, 20392-5420; bdm@draco.usno.navy.mil, wih@draco.usno.navy.mil

and

Lewis C. Roberts, Jr.[2]
Rocketdyne Technical Services, 535 Lipoa Parkway, Suite 200, Kihei, HI 96753; lroberts@premier.mhpcc.af.mil
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ABSTRACT

We present results of a search for faint companions to nearby ($d < 25$ pc) solar-like (F and G spectral type) stars using the natural guide star adaptive optics system on the Mount Wilson 100 inch (2.5 m) telescope during the period from 1996 June to 1999 August. The observing list, based on the third edition (1991) of the Catalogue of Nearby Stars by Gliese and Jahreiss, at present has 416 entries. To date, about 20% of the objects have been observed under varied seeing conditions. We have detected faint visible companions to five of the stars: HD 144287, μ Her A, HR 7123, 16 Cyg A, and HD 190067. The companions of three of these—μ Her A, HR 7123, and HD 190067—are new discoveries.
Key words: stars: individual (HD 144287, HD 190067, μ Her A, HR 7123, 16 Cyg A)

1. INTRODUCTION

The Center for High Angular Resolution Astronomy (CHARA) has been a key player in the field of binary star astronomy for over two decades, developing the technique of full-aperture speckle interferometry into an efficient and robust tool for binary star research (McAlister et al. 1987). However, speckle interferometry has its limitations. By comparing null-result speckle observations with positive-result lunar occultation observations (Mason 1994), one finds that the magnitude difference threshold for companion detection using speckle interferometry at visual wavelengths is approximately 3.

To push the magnitude difference threshold further, one needs a new technique. As well-designed natural guide star adaptive optics (NGS-AO) systems have become available for general astronomical use (Shelton et al. 1995), we saw an opportunity to improve the detection limit of binary star searches. Having been granted time on the Mount Wilson 100 inch (2.5 m) telescope NGS-AO system, we assembled a list of 416 stars within 25 pc of the Sun, brighter than $m_V = 10$, of F and G spectral types, and within the declination range of the telescope and the NGS-AO system ($-22°$ to $+58°$), by using the third edition of the Catalogue of Nearby Stars (Gliese & Jahreiss 1991) as source.

2. OBSERVATIONS

2.1. *NGS-AO System*

In 1994 January construction began on an NGS-AO system at the Cassegrain focus of the Mount Wilson 100 inch telescope. The system features a Shack-Hartmann wave front sensor driving an ITEK 241 actuator-deformable mirror. The heart of the wave front sensor is a front-side illuminated, 32 × 32 CCD array with 32 skipper output amplifiers. This arrangement allows frame rates up to 3.3 kHz. The wave front sensor processing chain employs eight Texas Instruments 320-C40 digital signal processors hosted in a Pentium-class machine running OS/2. The user interface allows complete remote operation of all adjustable optics and electronics and is designed for one-person operation. Further details can be found in Shelton et al. (1995) and Turner, ten Brummelaar, & Mason (1999).

2.2. *Observing Strategy*

We have developed a strategy that involves a long-exposure image (which usually saturates the primary) of a square field approximately 22″ on a side and centered on the main star. Since the blooming from the CCD masks any information near the main star, we take a sequence of up to 100 exposures of the main star and the immediate vicinity. To save time, we read out only that section of the CCD. In this detection phase, only the Johnson-Cousins I band is used. The next phase is a follow-up of any suspected stars with faint companions with in-depth observations in the Johnson-Cousins I, R, V, and sometimes B bands. This strategy allows us to detect companions in the separation range of 0″.2 to 10″ with a dynamic range of up to 9 mag.

2.3. *Data Reduction and Calibration*

In reducing the data, all images were debiased and flat-fielded in the conventional way. For the sequence of images, a weighted shift-and-add algorithm was used to create the final image. The weighted shift-and-add algorithm (ten Brummelaar et al. 1998) is a modification of the traditional image-stacking algorithm that takes the seeing conditions in each individual frame into account. The frames with

[1] Based on observations from Mount Wilson Observatory, operated by the Mount Wilson Institute under an agreement with the Carnegie Institution of Washington.

[2] Formerly with the Center for High Angular Resolution Astronomy, Georgia State University.

higher peak values (which represent better seeing) influence the final image more than frames with lower peak values. The fitting algorithm is described in detail in ten Brummelaar et al. (2000). In short, the point-spread function (PSF) used to represent the system performance is that of the primary star in the image, with a few modifications; near the primary, the PSF is a pixel-for-pixel table of numbers, while farther out the PSF is a radially symmetric series of values. This PSF is fitted to the primary and secondary components and reiterated until the intensity ratio converges.

Image-scale calibration was done by observing several long-period binary stars and calculating the best fit of CCD orientation and image scale via a least-squares approach. This left us with an uncertainty of about 0°.5 in position angle and about 3% in image scale. Since most of the PSFs were not radially symmetric in the center, additional errors in the astrometry undoubtedly crept in during the fitting process. The best values to use for astrometry are the I-band images, which have the most symmetric PSFs.

3. RESULTS

3.1. *Stars with No Detected Companions*

A full treatment of the null detections will be deferred to the second installment of data. The present batch of data was taken under highly variable conditions of seeing, transparency, and intrinsic system throughput. To date we have observed 51 of the 416 stars by using the long-exposure, full-frame technique, and 79 of the 416 stars using the short-exposure, subframe technique.

3.2. *Stars with Detected Companions*

Table 1 presents the results for stars for which we have seen companions. Figure 1 shows contour plots of five of the detections. We describe each of these stars in the following sections.

TABLE 1

POSITION ANGLES, SEPARATIONS, DIFFERENTIAL MAGNITUDES, AND FILTERS

Date (BY)	P.A. (deg)	Separation	Δm	Filter
Gl 609.2 HD 144287				
1996.5016......	255 ± 1	0.40 ± 0.01	3.05 ± 0.29	*I*
Gl 695A = HD 161797 = μ Her A				
1998.5359......	167 ± 3	1.42 ± 0.04	7.26 ± 0.15	*I*
1998.5360......	164 ± 3	1.43 ± 0.04	9.29 ± 0.15	*R*
Gl 732.1 = HD 175225 = HR 7123				
1996.4964......	112 ± 1	1.10 ± 0.03	4.19 ± 0.11	*I*
1998.4814......	104 ± 1	1.11 ± 0.03	4.07 ± 0.29	*I*
1998.4814......	105 ± 2	1.14 ± 0.03	6.29 ± 0.37	*V*
1999.4917......	101 ± 1	1.07 ± 0.03	4.13 ± 0.12	*I*
Gl 765.1A = HD 186408 = 16 Cyg A				
1998.5333......	204 ± 3	3.51 ± 0.11	7.00 ± 0.19	*I*
1998.5334......	209 ± 3	3.41 ± 0.10	8.64 ± 0.11	*R*
Gl 775.1 = HD 190067				
1996.5020......	82 ± 2	2.86 ± 0.09	5.37 ± 0.20	*I*

3.2.1. *HD 144287*

Wilson (1963) considered this star to be a spectroscopic binary on the basis of the range of radial velocities reported by observers from the David Dunlap and Mount Wilson observatories. The first spectroscopic orbit was determined by Duquennoy & Mayor (1991), who found $P = 12.19$ yr, $e = 0.68$, and $K = 5.3$ km s^{-1}, along with a mass function of 0.269 ± 0.0019 $M_\odot$. Their orbit is very well sampled to confirm the high eccentricity, and they suggested that the system might be resolvable by speckle interferometry. Speckle observations at visible wavelengths have been reported on a number of epochs by Bonneau et al. (1986) and by Mason et al. (1999) with no detection of a companion. However, Duquennoy et al. (1992) did report the detection of a companion using K-band speckle interferometry with the KPNO 4 m telescope and indicated that $\Delta K = 2$ mag. Their individual speckle measurements have not been published, but Duquennoy et al. used them to estimate an orbital semimajor axis of 0".25 and masses of 0.8 and 0.3 $M_\odot$. HD 144287 is a high proper-motion star with space velocity components $(U, V, W) = (104, -14, 16)$ (Eggen 1998). The solution for the *Hipparcos* parallax of 46.56 ± 0.89 required the inclusion of acceleration terms indicative of the presence of a long-term companion. The companion we have observed is most likely the same as that reported by Duquennoy et al. (1992). No additional companions are recorded in the Washington Double Star Catalog (Worley & Douglass 1997), hereafter WDS.

3.2.2. *μ Her A*

HR 6623 = HD 161797 = μ Her is a nearby multiple star consisting of the wide AB visual pair, μ^1 Her and μ^2 Her, having a photovisual $\Delta V = +6.14$ (Strand & Kallarakal 1997). The A component, μ^1 Her, has $V = +3.41$. The B component, μ^2 Her, is itself binary with a well-determined orbital period of 43.2 yr (Couteau 1960) and estimated apparent magnitudes of 10.3 and 10.8. The WDS lists a fourth distant component with $V = +11.5$, although its physical connection to the system is questionable.

Cochran & Hatzes (1994) detected a drift in radial velocity for μ^1 Her amounting to a decrease in velocity of ~ 150 m s^{-1} over an interval of ~ 1600 days. Cumming, Marcy, & Butler (1999) confirmed this drift, finding a slope of -47 ± 0.4 m s^{-1} yr^{-1}, in good agreement with Cochran & Hatzes. A periodogram analysis led Cumming et al. to predict an orbital period of 30 yr, at the limit imposed by sampling considerations, with a false-alarm probability of less than 1%.

Torres (1999) included μ^1 Her in an analysis of four systems showing measurable slopes in velocity and calculated predicted angular separations for specific secondary masses. His Monte Carlo calculations incorporated a random probability distribution for orbital inclination along with an eccentricity distribution based on observational results. Within these constraints, our measurement of the angular separation for μ^1 Her Aa, Ab is at the substellar mass transition (80 $M_{\rm Jup}$) predicted by Torres, 1".4.

We have measured the magnitude difference at the I band of $+7.3$ mag. The spectral type of μ^1 Her is G5 IV, for which $V-I = +0.95$ (Cox 1999). Thus $I_{Aa} \sim (+2.4)$ and $I_{Ab} \sim (+9.7)$. The *Hipparcos* distance of the system is 8.4 pc, corresponding to a distance modulus of -0.38. These values lead to absolute magnitudes of $M_{V_{Aa}} = +3.8$ and $M_{I_{Ab}} = +10.1$. Lacking a color for the secondary, we can

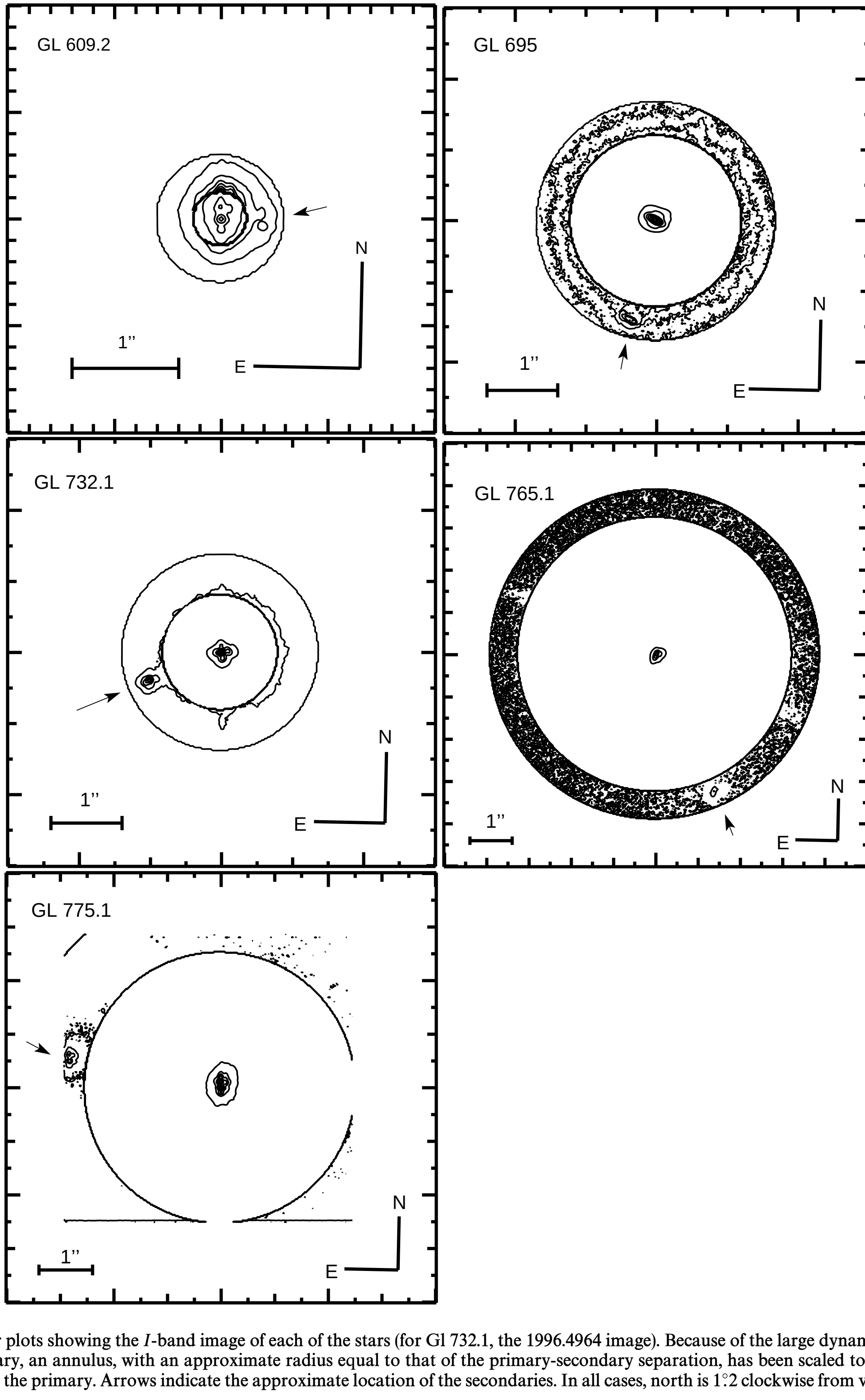

FIG. 1.—Contour plots showing the *I*-band image of each of the stars (for Gl 732.1, the 1996.4964 image). Because of the large dynamic range between the primary and secondary, an annulus, with an approximate radius equal to that of the primary-secondary separation, has been scaled to give the secondary a peak value similar to the primary. Arrows indicate the approximate location of the secondaries. In all cases, north is 1°.2 clockwise from vertical.

only estimate the transformation back to absolute visual magnitude. Assuming the star is an M dwarf, $2.2 \leq V-I \leq 4$. Thus, $+12.3 \leq M_{V_{Ab}} \leq +14$. The star must be no earlier in spectral type than M5 and could be significantly cooler. Our observation is therefore consistent with the companion to μ^1 Her being at the substellar mass transition. Further astrometric and color measurements are clearly of great interest.

3.2.3. *HR 7123*

On the basis of its space velocity, this late G subgiant has been associated with a moving group containing α Centauri

A, B, Proxima Centauri, and ten other stars (Anosova, Orlov, & Pavlova 1994). No companions are listed in the WDS, and the star was inspected for duplicity in a speckle survey of bright stars with null results (McAlister et al. 1987). In their CORAVEL survey, Duquennoy & Mayor (1991) found modest velocity variations indicative of a possible companion in a long-period orbit. We suggest that this previously unseen companion corresponds to that indicated by the radial velocity trends.

We measured magnitude differences in both I and V bands, allowing us to calculate the quantity $(V-I)_2 - (V-I)_1 = 2.2 \pm 0.4$. For the G9 IV primary component, we adopt $(V-I)_1 = 1.1 \pm 0.1$ (Cox 1999). From these two values, we derive the color of the secondary to be $(V-I)_2 = 3.3 \pm 0.4$, which corresponds to a dwarf of spectral type M2 or later. The *Hipparcos* parallax of 0''.0383 corresponds to a distance modulus of +2.1 mag, which combines with the V magnitude of the primary star and our ΔV to give a V absolute magnitude for the new companion of +9.7, consistent with a star of spectral type M2 V. The consistency between the color of the secondary and its deduced absolute magnitude argue strongly that the companion is physical rather than optical.

3.2.4. *16 Cyg A*

Its wide visual companion, 16 Cyg B, is now well known as a candidate planetary system with a highly eccentric orbit (Cochran et al. 1997). In spite of observations covering less than 1% of the very long-period orbit of the AB system, Hauser & Marcy (1999) (hereafter HM) have analyzed the velocity and astrometric data available for the pair, placing wide constraints on the possible orbital period. They also report the discovery of a companion to A by D. Trilling and his collaborators. While no measurements of (θ, ρ) have yet been published, it is clear from the description by HM that the measurement we present here is that of Trilling's companion. HM find no evidence of curvature in the astrometric measurements that might arise as the result of a submotion from a component Aa, placing constraints on the properties of the "companion." Trilling (2000, private communication) reports that follow up astrometric and photometric measurements indicate that the star is a background object.

From our observations of the magnitude differences at the I and R bands combined with the observed value of $R-I$ for 16 Cyg A found in the Yale Bright Star Catalogue (Hoffleit & Jaschek 1982), we derive $(R-I)_{Aa} = +2.0 \pm 0.3$, corresponding to a star of very late spectral type. Based on the magnitude and spectral type of the primary and a corresponding value for $(R-I)_A$ (Cox 1999), the apparent magnitude of the secondary at R band is $+14.1 \pm 0.2$. With a distance modulus of +1.67 magnitudes derived from the *Hipparcos* parallax, the absolute magnitude at R of the secondary, if it is physically associated with the primary star, would be +12.4. Because $V-R \geq +2$ for such an object, the absolute V magnitude of the secondary would be greater than +14.5. Such a secondary would be an extremely cool, low-mass object. A more plausible explanation, which is also compatible with our value of $(R-I)_{Aa}$, is that the secondary is a very late-type halo giant nearly 1000 times more distant than 16 Cyg A.

3.2.5. *HD 190067*

The WDS lists no companions for this G7 V disk population star (Eggen 1987). Duquennoy & Mayor (1991) found the star to have constant radial velocity within the errors of their measurements. Presently available information is thus insufficient to judge whether our newly reported companion is physical or optical.

4. CONCLUSION

We have detected companions to five nearby stars using the natural guide star adaptive optics system at the Mount Wilson 100 inch telescope. The companion to HD 144287 probably corresponds to the spectroscopic binary whose orbit was determined by Duquennoy & Mayor (1991) and that was subsequently seen using IR speckle imaging by Duquennoy et al. (1992). The new components of HD 161797 and HD 175222 have been suggested by trends in radial velocity and may therefore be physical in nature. The companion to 16 Cyg A was seen independently by Trilling just before our detection, and our data are not unsupportive of his conclusion that the secondary is optical rather than physical. No supporting information exists for the newly detected companion of HD 190067, and so it is premature to judge whether or not it is a gravitationally bound system. The proper motions of all these stars are sufficiently large to permit rather quickly the detection of rectilinear motions arising from optical companions.

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