Solar System Explorers 03

1. What are the three fundamental molecules that form gases, liquids, and ices in the Solar System?

2. What is the mass ratio of Jupiter to Saturn, 30:1, 10:1, or 3:1?

3. Which two planets do not have internally generated magnetic fields today?

4. What technique is the best for measuring the masses of the Jovian planets and their moons?

5. Do protoplanetary disks last roughly $10^7$, $10^8$, or $10^9$ years?

B. Name any moon of Uranus.
1. What are the three fundamental molecules that form gases, liquids, and ices in the Solar System?
   \[ \text{CH}_4, \text{NH}_3, \text{H}_2\text{O (also N}_2) \]

2. What is the mass ratio of Jupiter to Saturn, 30:1, 10:1, or 3:1?
   \[ 3:1 \]

3. Which two planets do not have internally generated magnetic fields today?
   \[ \text{Venus and Mars} \]

4. What technique is the best for measuring the masses of the Jovian planets and their moons?
   \[ \text{spacecraft tracking data} \]

5. Do protoplanetary disks last roughly $10^7$, $10^8$, or $10^9$ years?
   \[ 10^7 \text{ years} \]

B. Name any moon of Uranus.
   \[ \text{Juliet, Portia, Puck, Miranda, Ariel, Umbriel, Titania, Oberon …} \]
Solar System Formation II
Condensation to a Solar System

I. molecular cloud core before $t = 0$

II. freefall collapse $t = 0.1$ to $1$ Myr

III. protostar / disk evolution $t \sim 1$ to $10+$ Myr

IV. baby star / clearing / planet building $t \sim 100$ Myr

V. evolution of Solar System $t > 100$ Myr
Orion Proplyd

Edge-On Protoplanetary Disk
Orion Nebula
PRC95-45c · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O’Dell (Rice University), NASA

HST · WFPC2
HL Tau by ALMA

K9 T Tauri star
$V = 15.1$
1 million years old

$\sim 150 \text{ pc (no } \pi)\$

disk size $\sim 120 \text{ AU}$

resolution 35 mas

… about 5 AU
IRAS (1983): The Turning Point

IRAS excesses at 12, 25, and 60 microns over stellar photosphere

Aumann (1985) gives nice statistics of IRAS catalog:

- 756 sources corresponding to stars
- 504 dwarfs or subgiants
- 267 have 12 and 25 micron fluxes
- 36 have 12, 25, and 60 micron fluxes

- 12 are “Vega-like” with significant 60 micron fluxes
- 14% of A-type stars (N = 6)
- 3% of F-type stars (N = 4)
- < 1% of G/K-type stars (N = 2)

detecting protostellar disks or cold debris disks?
Beta Pictoris Disk

A5V star, 19.3 pc, ~20 Myr old

brightest infrared excess of any main sequence star detected by IRAS

circumstellar debris disk first imaged by Smith & Terrile (1984)
disk almost edge on, extends beyond 2000 AU (!) at optical wavelengths

temperature/color profile indicates large blackbodies not present
  … particles are inefficient radiators with size ~1 micron
two (or more) disks, clearing within 80 AU (inner void from 10 micron flux)
  … ice sublimates in inner disk, leaving refractory grains, or planet clearing?
emission intensity transition at 100 AU
  … models indicate albedo ~0.35 for grains in outer disk

bottom line: beta Pic has (at least) double disk, cleared in 20 Myr
Beta Pictoris Disk

MIRLIN map:
15 AU ring tilted
40 AU ring opp. tilt
65 AU ring asymmetric

STIS image:
warp in disk is real
(exaggerated here)
Beta Pictoris Disk Model

model must match:
brightness
color (temps)
inclination
extent
(don’t forget star)
80 deg

89 deg
Beta Pictoris Matching
outer ring structure from different temp samples
stellar photosphere fades (but still there)
dust brightens
disk stretches
central star has excess flux … hot dust in close!
HR 4796A Disk Details

A0 star, 67 pc, ~10 Myr old

circumstellar disk discovered by Koerner et al. (1998)
  … disk inclined by 72 deg
emission intensity increases (!) with radius, implying inner hole 40-70 AU
  … clearance out to Kuiper Belt?
ring width is < 17 AU from NICMOS observations
  … corresponding to thin Kuiper Belt, or shepherding planets?
dust beyond clearing could be due to smashing comets

8.8/10.3/12.5 micron flux excess implies inner disk with T ~ 160 K at ~10 AU
  … similar temp to zodiacal dust in our Solar System

bottom line: HR 4796A has double disk in a transition state at 10 Myr
  … between massive protostellar disks and more tenuous debris disks
## The IRAS Fab Four

<table>
<thead>
<tr>
<th>Name</th>
<th>SpType</th>
<th>L (suns)</th>
<th>distance (pc)</th>
<th>age</th>
<th>i (deg)</th>
<th>r&lt;sub&gt;in&lt;/sub&gt; (AU)</th>
<th>r&lt;sub&gt;out&lt;/sub&gt; (AU)</th>
<th>T&lt;sub&gt;dust&lt;/sub&gt; (K)</th>
<th>M&lt;sub&gt;dust&lt;/sub&gt; (Moons)</th>
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<tr>
<td>Vega</td>
<td>A0V</td>
<td>60</td>
<td>7.8</td>
<td>200 Myr</td>
<td>85</td>
<td>80</td>
<td>120</td>
<td>80</td>
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<td>Fomalhaut</td>
<td>A3V</td>
<td>13</td>
<td>7.7</td>
<td>200 Myr</td>
<td>&lt; 30</td>
<td>100</td>
<td>140</td>
<td>40</td>
<td>1.4</td>
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<tr>
<td>beta Pic</td>
<td>A5V</td>
<td>9</td>
<td>19.3</td>
<td>20 Myr</td>
<td>&gt; 80</td>
<td>20</td>
<td>2000+</td>
<td>85</td>
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<tr>
<td>eps Eri</td>
<td>K2V</td>
<td>0.3</td>
<td>3.2</td>
<td>500 Myr</td>
<td>70</td>
<td>50</td>
<td>80</td>
<td>35</td>
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## A New Member

| HR 4796A | A0     | 18       | 67            | 10 Myr    | 72     | 55                  | 80                  | 65:                 | ?                      |
Disk Photo Gallery

Image Gallery of Circumstellar Dust Disks

multi-wavelength study crucial
optical: stellar photosphere
near-IR: warm dust
far-IR: cool dust
sub-mm: very cold dust
radio: molecular contents
high resolution
flows
IV. Baby Star / Planet Building

THE STAR

core temp reaches $10^6$ K, deuterium burns…$10^7$ K, H burns

T Tauri phase --- bipolar outflow, gas cleared

HH objects --- gas jettisoned

disk details become visible --- gaps? warps?
Clearing of Debris

HH-30 (Herbig-Haro object) disk 225 AU across knots moving at 200 km/sec
IV. Baby Star / Planet Building

THE PLANETS

buildup of terrestrial planets took ~ 100 Myr
slow accumulation of small bodies
not much mass involved

buildup of giant planets took ~ 10 Myr (need to have gas around)
all giant planets have roughly the same heavy element mass…
  5, 15, 300, 300 X solar heavy/light element ratios in J/S/U/N

H and He total mass varies by a factor of 100!
fraction of total mass: 90% J, 75% S, 10% U, 10% N

PAPER TOPIC: Why two kinds of giant planets?
Clearing of Debris

GAS

“DUST”
Continuous Cleaning Required
V. Evolution of Solar System

the fat lady has NOT sung …
V. Evolution of Solar System

continuous bombardment (craters, oceans, regolith)
giant impacts (Moon origin, Venus retrograde?, Uranus tilt?)
tidal locking of moons (many)
resonances that cause evolution (Io-Eur-Gany, Kirk gaps, Plutinos)

“the Nice Model”
happens in the first ~10 million years
The Nice Model

problem: Jupiter, Saturn, Uranus, Neptune
        NOT in circular, coplanar orbits

<table>
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<tr>
<th></th>
<th>$a$ (AU)</th>
<th>$e$</th>
<th>$i$ (deg)</th>
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<tbody>
<tr>
<td>Jupiter</td>
<td>5.20</td>
<td>0.048</td>
<td>1.30</td>
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<td>Saturn</td>
<td>9.54</td>
<td>0.056</td>
<td>2.49</td>
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<tr>
<td>Uranus</td>
<td>19.19</td>
<td>0.046</td>
<td>0.77</td>
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<tr>
<td>Neptune</td>
<td>30.07</td>
<td>0.009</td>
<td>1.77</td>
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</table>

solution: wandering giant planets (Tsiganis et al. 2005)
          interactions with disk of planetesimals
The Nice Model

details: start with 4 Jovians with $e$ and $i \sim 0.001$

  - Jupiter    5.45 AU
  - Saturn    < 8.65 AU (1:2 resonance)
  - Ice Giant 1  11-13 AU
  - Ice Giant 2  13.5-17 AU

add 1000-5000 bodies with total mass 30-50 Earths
located beyond Jovians, extends to 30-35 AU

EVOLVE!

Jupiter moves in
Saturn and Ice Giants move out
The Nice Model

Jup:Sat resonance 1:2 strongest ... kaboom!
Ura/Nep swap in 50% of simulations

Tsiganis et al. 2005
migration stops when
disk nearly depleted
→ present day

green: today
gray: 0 Sat-IG encounters
black: ≥ 1 Sat-IG encounter

more disk mass?
more stability
Jup-Sat too far apart
final $e$ too small

Tsiganis et al. 2005
The Nice Model

“Our model statistically reproduces all aspects of the orbits of the giant planets. \([a, e, i \text{ for Jup/Sat/Ura/Nep}]\)

It is consistent with the existence of regular satellites,

with the observed distributions of Jupiter’s Trojans,

perhaps with the existence of Neptune’s Trojans, and

does not contradict the distribution of main-belt asteroids.”

Tsiganis et al. 2005
V. Evolution of Solar System

continuous bombardment (craters, oceans, regolith)
giant impacts (Moon origin, Venus retrograde?, Uranus tilt?)
tidal locking of moons (all over)
resonances that cause evolution (Io-Eur-Gany, Kirk gaps, Plutinos)

"the Nice Model"
* happens in the first ~10 million years *

captures (asteroids, Triton)
changing atmospheres (Venus, Earth, Mars, Titan, Pluto)
ring systems/toroids (Io)
icecaps (Mercury, Earth, Moon, Mars)
erosion (Earth, Mars)
vulcanism (Venus, Earth, Mars, Io, Enceladus, Triton)
life