EXTRASOLAR PLANETS: TECHNIQUES, RESULTS, AND THE FUTURE

G.W. MARCY
San Francisco State University & UC Berkeley
Dept. of Physics and Astronomy, SFSU, San Francisco, CA, USA 94132, gmarcy@stars.sfsu.edu

AND

R.P.BUTLER
Anglo-Australian Observatory
PO Box 296, Epping, NSW 2121 Australia, paul@aaoepp.aao.gov.au

1. Introduction

To date, we have not obtained direct images of planets around other stars. However, the small–amplitude Keplerian motion of stars, presumably caused by the gravitational forces exerted them by planets, now provides information on their masses and orbits. The first extrasolar planetary system was found around a neutron star, the 6.2–millisecond pulsar PSR 1257+12 (Wolszczan & Frail 1992, Wolszczan 1998). Its three terrestrial–mass companions indicate the ubiquity and diversity of planetary systems. The leading model for the formation of the pulsar planets involves the post–supernova recapture of material, perhaps from a pre–existing stellar companion, into an accretion disk. The accumulation of dust grains into the pulsar planets may have occurred by processes similar to the formation of rocky planetary cores in our Solar System. The existence of pulsar planets suggests that planet formation is robust and depends little on specific disk properties, as long as adequate heavy elements are present (Wolszczan 1998).

The discovery of a Doppler periodicity in 51 Peg by Mayor and Queloz (1995), followed soon thereafter by periodicities for 47 UMa and 70 Vir (Butler & Marcy 1996, Marcy & Butler 1996), seems to constitute the first detections of jupiter–mass companions to Solar-type stars. Any physical kinship of these companions to the "planets" in our Solar System must stem from the measured distributions of masses and orbital elements, along with models of formation. The models are undergoing rapid elaboration, as the diversity of Jupiter–mass companions reveals more complexity than was suggested by our orderly Solar-System architecture.

Doppler surveys of main sequence stars have revealed 17 companions to main sequence stars that are extrasolar planet candidates. Among these candidates, 15 have $M \sin i < 5$ $\mathrm{M_{JUP}}$ and constitute the best planet candidates. Here, $M \sin i$ represents the product of companion mass, M, and the (unknown) sine of the orbital inclination, i, where i=90 deg represents an orbit viewed edge–on. In addition, four main sequence stars are known to harbor Doppler companions that have $M \sin i$ = 15–75 $\mathrm{M_{JUP}}$, which may represent the "brown dwarfs" (Mayor et al. 1998, Mayor et al. 1997).

The distinction between "planets" and "brown dwarfs" remains cloudy and rests on two formation scenarios. Planets form out of the agglomeration of condensible material in a disk into a rock–ice core (eg. Lissauer 1995). In contrast, brown dwarfs presumably form by a gravitational instability in gas (eg. Boss 1998, Burrows et al. 1998). Hybrid formation scenarios remain viable in which the relative importance of solid core growth and gas accretion within a disk lead to a continuum in internal structure. Subsequent collisions may lead to further growth and dynamical evolution. Some researchers prefer to differentiate planets from brown dwarfs based on mass alone, at 13 $\mathrm{M_{JUP}}$, below which Deuterium does not ignite (Burrows 1997). By either distinction of planets from brown dwarfs, this semantic segregation may explain the physics of substellar objects no more fully than "spiral" and "elliptical" summarize the physics of galaxies.

The most important statistical property of the substellar companions is their mass distribution. Companions having $M \sin i$ in the decade between 0.5–5 $\mathrm{M_{JUP}}$ outnumber those between 5–50 $\mathrm{M_{JUP}}$ by a factor of $\sim$3 (eg, Marcy & Butler 1998, Mayor et al. 1998). The poor detectability of the lowest–mass companions implies that the factor of 3 is a lower–limit to the cosmic ratio. This abundance of companions having Jovian masses suggests that distinct formation processes predominated, arguably similar to those associated with the giant planets in our Solar System (Lin et al. 1998).

The host stars of the extrasolar planet candidates have higher mean metallicity by a factor of $\sim$2 in abundance compared with field stars (Gonzalez 1998, Gonzalez et al. 1998). Equally interesting is that seven planets reside in orbits with a radius less than 0.12 AU, sometimes termed "51 Peg" planets (Mayor & Queloz 1995, Butler et al. 1998). These small orbits challenge us to explain their existence in a region where both the high temperatures and the small amount of protostellar disk material would inhibit formation *in situ.* The 51 Peg planets thus offer support for the prediction by Goldreich & Tremaine (1980) and by Lin (1986) that Jupiters may migrate inward from farther out (Lin et al. 1995, Ward 1997, Trilling et al.

1998).

Perhaps most intriguing about the planet candidates are the orbital eccentricities. The orbits of the 51 Peg planets may suffer some tidal circularization (Lin et al. 1998, Terquem et al.1998, Ford et al. 1998, Marcy et al. 1997), and indeed their orbits are all nearly circular (see Table 1). In contrast, the planets that orbit farther than 0.15 AU from their star all reside in non–circular orbits having e >0.1, i.e. more eccentric than for Jupiter (e=0.05). Indeed, all but two have e >0.2 . This high occurrence of orbital eccentricity has lead to a variety of models in which Jupiter–like planets suffer gravitational interactions with a) other planets (Weidenschilling & Marzari 1996, Rasio & Ford 1996, Lin & Ida 1996, Levison et al. 1998), b) the disk (Artymowicz 1998), c) a companion star (Holman et al. 1996, Mazeh et al. 1997), and d) passing stars in the young cluster (de la Fuente Marcos and de la Fuente Marcos 1997, Laughlin and Adams 1999).

2. The Doppler Detection Technique

All of the orbiting planet candidates found to date were identified by precise Doppler measurements. Therefore we describe this technique in some detail here to illustrate its capabilities and limitations. The Sun "wobbles" around the Solar System center–of–mass at a speed of $\sim$13 m s^{-1} , due to its mutual orbit with Jupiter and Saturn (12.5 and 2.7 m s^{-1} , respectively).

The semi–amplitude, K, of the radial velocity of a star induced by its orbiting companion is:

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{m_{\rm p} \sin i}{(M_* + m_{\rm p})^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

where P is the orbital period, $m_{\rm p}$ is the mass of the unseen companion, M_* is the stellar mass, and e is the eccentricity. For randomly oriented orbital planes, $< \sin i >=\pi/4$. The period, P, can be eliminated with Kepler's third law, $P^2 = \frac{4\pi^2 a^3}{G(M_*+m_{\rm p})}$, where a is the semimajor axis of the orbit of the companion relative to the primary. Figure 1 shows lines of constant amplitude, K, for the reflex velocity for a Solar–mass star, in a two–parameter plane of orbital radius, a, and Msin i for the companion mass. A Jupiter–mass at 1 AU causes a reflex amplitude of 28.0 m s^{-1} $\times$ sin i, which is easily detectable.

Orbital periods that are shorter than the duration of the velocity measurements for a given star can be revealed by periodogram techniques to identify the periodicity in the velocities. Velocity amplitudes, K, can be detected which lie at or below the velocity measurement errors. But for orbital periods that are comparable to (or longer than) the duration of observations, experience shows that a confident detection requires that the

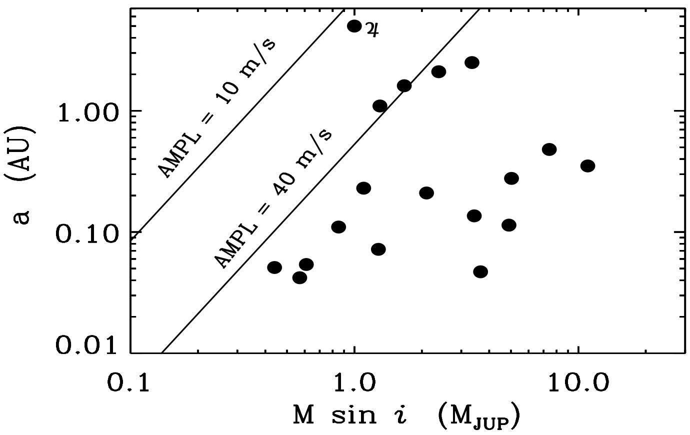

Figure 1. Detectability of companions by the Doppler technique for threshold velocities of 10 and 40 m s^{-1} . Known planet candidates are represented as dots.

amplitude be ~4× the Doppler error. The stringent demand stems from the many ways to be fooled, such as by photospheric noise, multiple companions, or the occasional 3–σ data point which will appear among a multitude of target stars. Thus, for a precision of 3 m s^{-1} , amplitudes of 12 m s^{-1} are just detectable for the case of long orbital periods. Therefore, from Figure 1, with a Doppler precision of 3 m s^{-1} , companions having 1 M_{JUP} at 5 AU are just detectable and as are saturn–masses at 1 AU.

The limit to the Dopper technique probably resides at a precision of 3 m s^{-1} , due to the intrinsic stability limit of stellar photospheres (Saar et al. 1998). Surface (photospheric) turbulence and pulsation could prevent detection of giant planets or produce false alarms. A detailed study of the velocity stability of F,G, and K dwarfs has been carried out by Saar and Donahue (1997) and Saar et al. (1997) who show that the photospheric flux spectra exhibit *intrinsic* velocity variability (not related to measurement errors) that depends on rotation period. For Solar-type dwarfs younger than 1 Gyr that rotate with $P_{\rm rot} < 10d$, the intrinsic stellar velocities scatter by over 10 m s^{-1} . For rotation periods of 10 to 30 d, typical of main sequence stars in the general field, the RMS velocity variability declines from 15 m s^{-1} to 3 m s^{-1} , respectively. The likely causes of the variability are spots rotating across the stellar disk and short–term magnetically–controlled fluid flows on the stellar surface. Single G, K, and M type main sequence stars that are older than 3 Gyr have photospheric spectra that flutter by less than 5 m s^{-1} RMS, sufficiently quiescent to detect jupiter twins.

Precise Doppler measurements by four teams have provided detections of companions plausibly below 10 M_{JUP} , namely by Cochran et al. (1997), Mayor & Queloz (1995), Noyes et al. (1997), and by Marcy & Butler (1998). Each team uses a somewhat different scheme for wavelength calibration, to eliminate the systematic Doppler errors. Mayor and Queloz (1995) use a stable, fiber–fed spectrometer, with a simultaneous Th-Ar lamp as wavelength calibration. An alternative approach is to pass the starlight through iodine gas, to superimpose a comb of absorption lines that convey the wavelength scale directly on the stellar spectrum (Butler et al. 1996). For iodine calibration, one must build a computer model of the composite (star and iodine) spectrum which includes a floating PSF and Doppler shift, in a least-squares fit to the observed spectrum. Resulting Doppler precision appears to be $\sim$10 m s^{-1} for all groups, but Butler et al. (1996) have achieved 3 m s^{-1} at Lick observatory on quiet stars. With this precision, Jupiter–mass planets at 5 AU will be detectable within a few years. We note that superior Doppler precision will not help, as the fundamental limit is set by the stability of the stellar photospheres at $\sim$3 m s^{-1} .

3. Doppler Results: Properties of the Candidate Planets

The Doppler technique has revealed 17 companions to main sequence stars which have $M \sin i < 15$ M_{JUP} , all listed in Table 1. This list is complete as of 1999 Jan 1 (taken from Cumming et al. 1999).

A glance at Table 1 shows that among the 17 planet candidates, 4 have semimajor axes greater than 1 AU. Two representatives of these long–period planet candidates may be examined in Figure 2 which shows the radial velocity versus time for 16 Cygni B and 47 Ursae Majoris, both Solar-type stars. In both cases the value of $M \sin i$ near 2 M_{JUP} . Also, the eccentricity is non–zero in both cases, 0.68 $\pm$0.03 for 16 Cygni B, and e=0.10 $\pm$0.03 for 47 UMa. Indeed all long–period planetary companions reside in eccentric orbits, compared to Jupiter and Saturn which both have e=0.05.

Nonetheless, the most compelling analog to Jupiter detected to date is the companion to 47 UMa (Butler and Marcy 1996). The velocities for 47 UMa exhibit one clear period of 3.0 yr, with a best-fit Keplerian eccentricity of e = 0.10 $\pm$ 0.03, as shown in Figure 2.

The velocity residuals have an rms of 8 m s^{-1} (and only 4 m s^{-1} since 1994 November), consistent with the errors. These residuals give no evidence for additional companions, nor for non–Keplerian motion. The semimajor axis of 2.1 $\pm$ 0.1 AU and the companion mass of 2.4 $\pm$ 0.1 / $\sin i$ seems marginally consistent with expectations that giant planets form beyond the ice-condensation distance, at least several AU from the host star (Lissauer 1995, Boss 1995). Orbital migration after formation may have

TABLE 1. Orbits and Masses of Extrasolar Planet Candidates

Star Name	Spec. Type	P (days)	a (AU)	K (m/s)	$M_p \sin i$ (M_J)	e	Reference
HD 187123	G3V	3.097	0.042	83	0.57	0.03	Butler et al. (1998)
τ Boo	F7V	3.31	0.047	468	3.66	0.00	Butler et al. (1997)
51 Peg	G5V	4.23	0.051	56	0.44	0.01	Mayor & Queloz (1995)
							Marcy et al. (1997)
Ups And[a]	F8V	4.62	0.054	71.9	0.61	0.15	Butler et al. (1997,99)
HD 217107	G7V	7.12	0.072	140	1.28	0.14	Fischer et al. (1999)
ρ^1 55 Cnc	G8V	14.7	0.11	75.9	0.85	0.04	Butler et al. (1997)
Gliese 86	K1V	15.8	0.114	379	4.9	0.04	Queloz et al. (1999)
HD 195019	G3V/IV	18.3	0.136	275	3.43	0.03	Fischer et al. (1999)
ρ CrB	G2V	39.6	0.23	67	1.1	0.11	Noyes et al. (1997)
Gliese 876	M4	61	0.21	217	2.1	0.27	Marcy et al. (1998)
							Delfosse et al. (1998)
HD 168443	G8IV	57.9	0.28	350	4.96	0.54	Marcy et al. (1999)
HD 114762	F7V	84.0	0.41	618	11.0	0.33	Latham et al. (1989)
							Marcy et al. (1999)
70 Vir	G2.5V	117	0.47	316	7.4	0.40	Marcy & Butler (1996)
HD 210277	G7V	437	1.20	42	1.28	0.45	Marcy et al. (1999)
16 Cyg B	G2.5	799	1.6	50.3	1.67	0.69	Cochran et al. (1997)
47 UMa	G0V	1092	2.1	47	2.38	0.11	Butler & Marcy (1996)
14 Her	K0V	>1620	>2.5	75	>3.3	0.36	Mayor et al. (1998)

[a]Probable 2nd companion, P=3.9 yr, e=0.58, $M \sin i$ =9.6 M_{JUP} (Butler et al. 1999)

brought 47 UMa b closer (Ward 1997, Trilling et al. 1998, Lin et al. 1999). Alternatively, 47 UMa b may have formed *in situ*.

For 16 Cyg B, the Doppler variations were detected independently at Lick and McDonald Observatories (Cochran et al. 1997), yielding similar orbital parameters. The velocity residuals, in both cases, are consistent with the measurement errors, with no indication of additional companions of jupiter–mass within 1 AU. The orbital parameters give P=803 $\pm$3 d, and eccentricity, e=0.687 $\pm$ 0.03 . The implied companion mass is M = 1.67 $\pm$ 0.1 M_{JUP} /sin i. This mass falls well within the range associated with "extrasolar giant planets", as defined structurally (Burrows et al. 1997).

The lithium abundance of 16 Cyg A is 5 times that of 16 Cyg B, despite their nearly equal masses and identical ages (King et al. 1996). The origin of this difference in Li–burning is not understood, but may result from the torque exerted on the star by the protoplanetary disk during the pre-main sequence phase (Strom 1994, Pinsonneault 1997, Martín 1997).

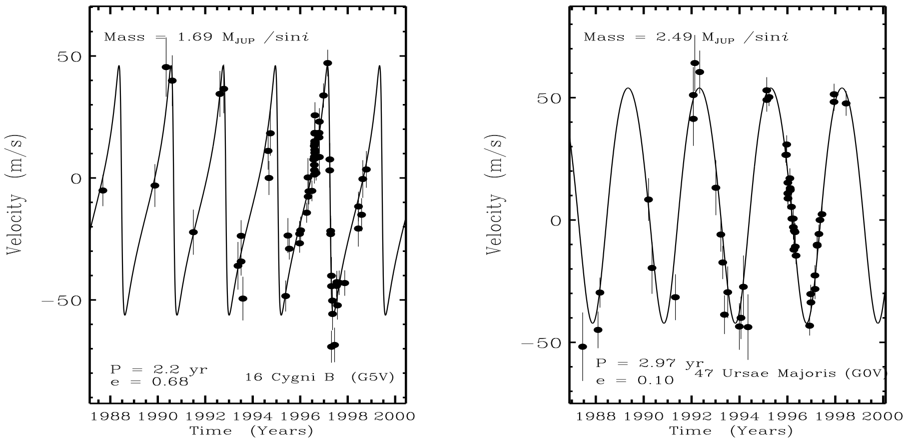

Figure 2. Measured velocity vs. time for two representative Jupiter–mass companions, 16 Cygni B (left) and 47 Ursae Majoris (right), in long orbits. The duration of the observations is 11 yr. The corresponding semimajor axes are 1.6 AU and 2.1 AU, and the eccentricities are 0.68 and 0.10, respectively. All 9 known Jupiter–mass companions that orbit beyond 0.2 AU reside in non–circular orbits.

For 16 Cyg B, the modest value of $M \sin i$ =1.7 M_{JUP} resides well below the lowest mass expected from "star formation" processes that produce brown dwarfs, though that mass limit remains poorly understood (Boss 1995). The orbital eccentricity of 16 Cyg B represents the first challenge to the predicted ubiquity of circular orbits for planets, with more violations soon to follow. Assuming that $\sim$2 M_{JUP} companions form in a dissipative disk, some dynamical process must have perturbed the original circular orbit.

3.1. GIANT PLANETS ORBITING WITHIN 0.1 AU

Eight jupiter–mass companions have orbital radii less than 0.15 AU (Table 1), often called "51 Peg" planets (Mayor & Queloz 1995, Butler et al. 1998, Marcy et al. 1997). Figure 3 shows the phased Doppler measurements for the two representative stars that apparently harbor short–period planetary companions.

These close jupiters may not represent the typical orbital positions of jupiter–mass planets, as detectability is enhanced by proximity to the star (Fig.1). Nonetheless, their existence raises possibility that inward orbital migration was important, as formation *in situ* seems unlikely (Lissauer

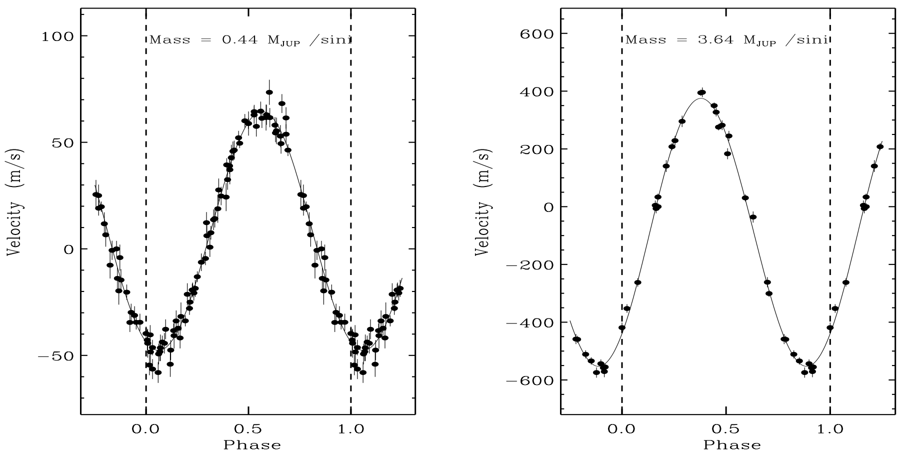

Figure 3. Measured velocity vs time for two representative Jupiter–mass companions, 51 Pegasi and τ Bootes, in small orbits with a= 0.05 AU. All 8 companions orbiting within 0.15 AU reside in nearly circular orbits, as evident from the sinusoidal velocity curves here. Tidal effects between the planet and star may circularize the orbit.

1995).

An upper limit to the mass of the companion to 51 Peg stems from its low X-ray flux (Pravdo et al. 1996). If the companion had a mass of more than 15 M_{JUP} , it would have tidally spun up the primary star, giving 51 Peg an active corona and a high X-ray flux, as seen for all tidally spun–up G Dwarfs (Marcy et al. 1997). It is plausible that the 51 Peg planets planets would have their orbits circularized theoretically on time scales of order 10^9 yr. (Rasio et al. 1996, Marcy et al. 1997, Terquem et al. 1998). Indeed all 51 Peg planets have low eccentricities, below 0.15 . Some of these planets may have their spins tidally locked to the orbit.

In particular, for τ Boo the sinusoidal Doppler variations yield a period, P = 3.3125 $\pm$ 0.0001 d, and eccentricity, e = 0.00 $\pm$ 0.01, and an amplitude of 470 m s^{-1} , implying a companion mass of 3.7 $M_{JUP}/\sin i$. The high companion mass and small orbital radius (a=0.045 AU), if correct, should force tidal synchronization of the *stellar rotation* with the orbit. Indeed, the spin period of τ Boo is 3–4 d from chromospheric diagnostics (Baliunas et al. 1997, Henry et al. 1997). Thus both the observed zero eccentricity and stellar spin period are consistent with (and demanded by) the existence of the companion around τ Boo.

Upsilon Andromeda has a Jupiter-mass companion with an orbital period of 4.6 d. If we subtract the orbital fit from the observed velocities, the residuals themselves appear periodic with a period of 3.9 yr, based on our velocities from 1987 to 1999. An orbital fit to these residuals yields $P = 3.9 \pm 0.2$ yr, e=0.58±0.1, K=195 m s^{-1} . The implied minimum mass of this putative companion is, $M \sin i$ = 9.8±1 $\mathrm{M_{JUP}}$ (Butler et al. 1999). Periastron passage last occurred on JD 2451177 (29 Dec 1998). Hipparcos astrometry revealed no astrometric wobble to the star, implying an upper limit for the mass of this outer companion of 13 $\mathrm{M_{JUP}}$. Thus, Upsilon Andromedae appears to harbor two companions, one of Jupiter mass and the other of 10–13 $\mathrm{M_{JUP}}$. Further observations are necessary, in addition to further work on the chromosphere of the star (Saar et al. 1998, Noyes et al. 1984, Baliunas et al. 1997).

3.2. MASS DISTRIBUTION OF PLANETARY COMPANIONS

Three Doppler surveys are complete enough to reveal the mass distribution of substellar companions from 0 to 70 $\mathrm{M_{JUP}}$ within 5 AU. These three surveys include the modest precision (300 m s^{-1}) survey of 570 GK dwarfs by Mayor, Duquennoy, and Udry (Duquennoy and Mayor 1991, Halbwachs et al. 1998). The other two are high–precision Doppler surveys of Mayor et al. (1997) and Marcy and Butler (1998) which surveyed 140 and 107 GK stars respectively. The first survey of modest precision revealed 10 "brown–dwarf" candidates, characterized by $M \sin i$ = 15 - 60 $\mathrm{M_{JUP}}$ (Mayor et al. 1997). However Hipparcos now enables the detection of wobbles for those cases in which the companion is massive enough and the semimajor axis is large enough that the wobble would be over a few milliarcsec. For every one of the 10 brown dwarf candidates for which the semimajor axis was large enough that a stellar companion could have been detected by Hipparcos, an astrometric wobble indicative of a pole–on orbital orientation was indeed seen. Thus, 7 of the 10 brown dwarf candidates have extreme values of $\sin i$, rendering the companion more massive than 0.075 $\mathrm{M_\odot}$.

The $M \sin i$ values for the surviving substellar candidates are shown in Fig. 4, drawn from all three surveys mentioned above. This histogram shows 8 companions in the mass bin from 0 – 5 $\mathrm{M_{JUP}}$ (i.e., those planet candidates from Table 1 which came from only these three surveys). From 5 – 10 $\mathrm{M_{JUP}}$, there is only one companion (70 Vir b). The remaining mass range from 10 – 70 $\mathrm{M_{JUP}}$ contains only 4 companions. The dearth of companions from 15-70 $\mathrm{M_{JUP}}$ is surprising. Equally remarkable is the remarkable spike in the mass distribution for masses from 0 – 5 $\mathrm{M_{JUP}}$, in contrast to the "desert" of brown dwarfs of higher mass. Those 4 brown dwarf candidates may also be H-burning stars, but their periods are too short to permit astrometric detection of the wobble even by Hipparcos.

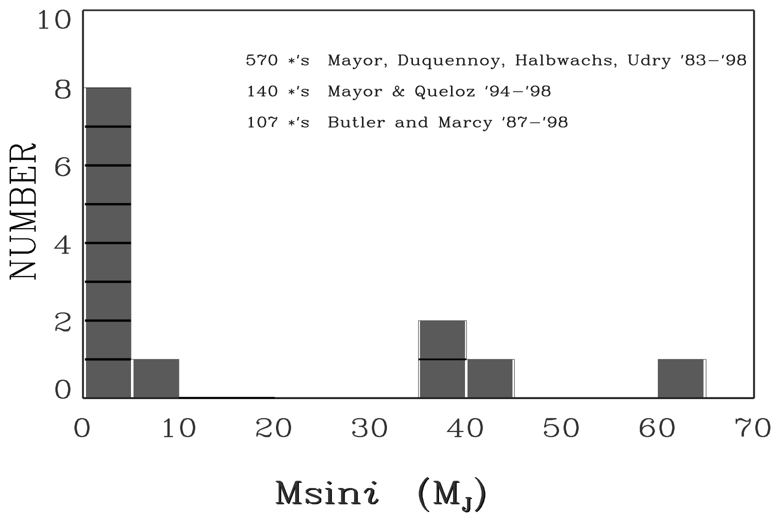

Figure 4. Histogram of $M \sin i$ for all companions found by the two Doppler surveys at Geneva Observatory and Lick Observatory. The distribution of $M \sin i$ exhibits a discontinuous spike at the lowest masses, 0–5 M_{JUP} . This discontinuity suggests the presence of a new population of Jupiter–mass companions distinct from the more massive brown dwarfs that have larger masses. The companions from 0–5 M_{JUP} plausibly represent planets, not unlike the giant planets in our Solar System. Seven companions were removed from this histogram, as Hipparcos revealed the wobble directly, forcing $M \sin i >$ 70 M_{JUP} , off scale.

Apparently, main sequence stars harbor more companions having masses below 5 M_{JUP} than from 5 - 70 M_{JUP} , within 3 AU. We note that all selection effects favor detection of the most massive companions. Therefore, the spike at low masses suffers incompleteness, and is likely to grow even taller as Doppler precision improves with time. This discontinuity in the mass distribution at 5 M_{JUP} suggests that two qualitatively different types of objects populate either side. A common nomenclature is found in the terms "planet" and "brown dwarf" for the two species. Clearly, the formation processes and internal structure for both types of substellar companions require further work. And it remains unknown to what extent the Jupiter–mass extrasolar companions share a physical heritage with the planets in the Solar System, if any.

A clue to any such relationship between extrasolar and Solar System planets may reside in the mass distribution. Figure 5 shows the histogram of Msini within the range 0<15 M_{JUP} for all known companions to main–sequence stars. The distribution of $M \sin i$ shows a rapid decline at roughly 4 M_{JUP} . There are no companions having $M \sin i = 7.5$–11 M_{JUP} and those

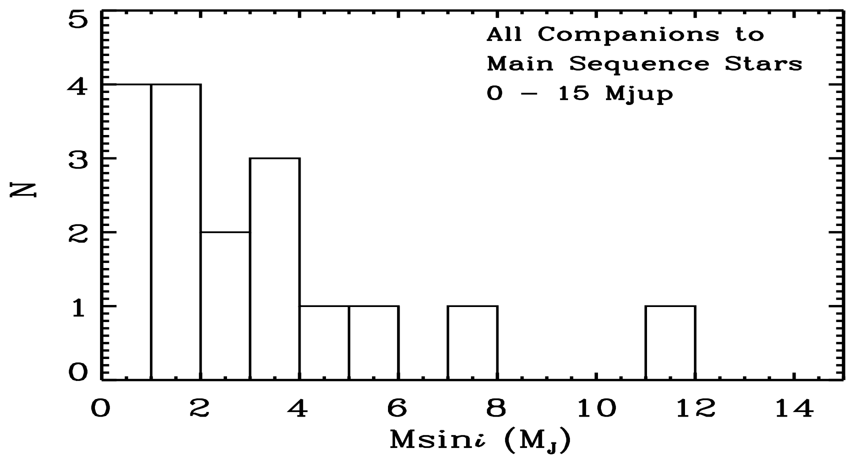

Figure 5. Histogram of $M \sin i$ for all companions from all surveys, within the range $M \sin i$ = 0–15 M_{JUP} . All selection effects favor the detection of more massive companions. In contrast, the observed distribution of $M \sin i$ exhibits a rise from ∼6 M_{JUP} toward smaller masses. Therefore, the actual mass distribution of companions must also rise. Apparently these companions represent the tip of the planet mass distribution.

massive companions would have been easily detected. This absence seems statistically significant relative to the 14 companions having $M \sin i$ =0.4–5 M_{JUP} as all selection effects favor detection of the high–mass companions. Even accounting for the Poisson fluctuations within the mass bins and for the detectability of the companions, the distribution of $M \sin i$ must drop from 3 to 7 M_{JUP} . This drop implies that the distribution of companion masses, dN/dM, must decline beyond ∼5 M_{JUP} , for companions within 2.5 AU. Apparently, the most massive planets contain ∼5 M_{JUP} , with at most a few exceptions.

The largest $M \sin i$ among planet candidates (Fig 5, Table 1) is for HD114762 which has $M \sin i$ =11.02 M_{JUP} , well above the proposed decline in the planetary mass function at ∼5 M_{JUP} . The unknown $\sin i$ leaves uncertain its true mass and its affiliation with "planets." This companion may have a mass that is close to the H–burning threshold of 0.1 $M_\odot$(Cochran et al. 1991, Hale, 1995).

3.3. SEMIMAJOR AXES OF JUPITER–MASS COMPANIONS

Prior to 1995, Jupiter–mass companions were expected to form and reside in circular orbits with a radius of ∼5 AU (Boss 1995, Lissauer 1995). Indeed,

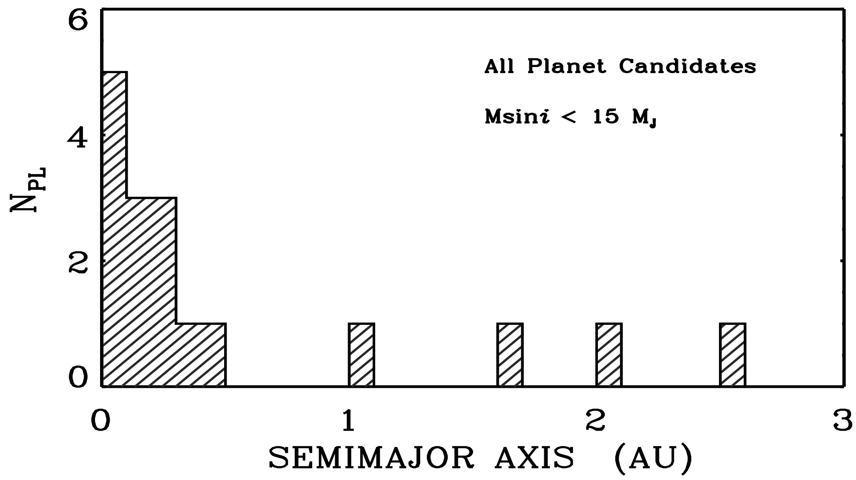

Figure 6. Distribution of semimajor axes among all planet candidates. Detection of small orbits is favored, due to larger wobble of the star, causing a selection effect for them. However there is a pile-up of companions close to the host star: 11 of 17 have a=0–0.3 AU, but only 2 of 17 have a=0.3–0.6 AU, and none 0.6–0.9 AU. Selection effects cannot explain this occurrence in small orbits (Cumming et al. 1999).

planet–search strategies and funding decisions prior to 1995 were biased toward this expectation, revealing the treacherous symbiosis between theoretical expectation and the design of experiments. In sharp contrast, among the 17 extrasolar planet candidates detected to date, 11 reside in orbits with $a < 0.3$ AU. Figure 6 shows the histogram of semimajor axes of all extrasolar planet candidates. The surprisingly small orbits stand in contrast to the prediction that the first step in the formation of giant planets involves coagulation of ice grains, which exist only beyond ∼3 AU. Such grain growth provides the supposed requisite solid core, around which gas could accrete. In retrospect, orbital migration or planet scattering may explain these close orbits (e.g., Lin et al 1999, Rasio & Ford 1996).

One must consider the selection effect that favors detection of close companions (Figure 1). Jupiter–mass companions within 0.1 AU clearly occur around ∼3% of Solar–type stars. But do jupiters occur preferentially in close? The preliminary indication is yes, at least for the field–of–view within 3 AU of the host star. Figure 6 shows that 11 of 17 planet candidates reside within 0.3 AU, and the remaining 6 are spread from 0.3–2.5

AU, revealing a remarkable density gradient. Regarding the selection effect, giant planets that reside 0.5 - 1.5 AU from their star would impart a reflex velocity of $25 - 40\,\mathrm{m\ s^{-1}}$ which is clearly detectable with current precision of $5\ \mathrm{m\ s^{-1}}$ (Figure 1). A precision better than $5\,\mathrm{m\ s^{-1}}$ has been achieved for 60 chromospherically quiet stars from Lick Observatory during the past 3 yr (Marcy & Butler 1998). None of the 60 stars exhibits a planetary-mass companion with a semimajor axis between 0.5 and 1.5 AU. Thus, the distribution of planetary semimajor axes contains an apparent maximum within 0.2 AU, in terms of $\mathrm{d}N/\mathrm{d}a$. It remains unknown whether there is a population of Jupiter–mass companions beyond 3 AU.

3.4. ORBITAL ECCENTRICITY OF JUPITER–MASS COMPANIONS

All 5 extrasolar planets orbiting closer than 0.1 AU have small eccentricities (Table 1). These eccentricities are much lower than that found in stellar binary systems, for which the median is 0.4 , with very few lower than e=0.1 (Duquennoy and Mayor 1991). Stellar binary systems with periods under 15 d are found empirically to circularize within ~5 Gyr.

Tidal circularization of orbiting planets may be due to dissipation in the planet rather than the host star. The tidal circularization time (due to dissipation in the planet) is given by Goldreich and Soter (1966):

$$\tau_{\mathrm{circ}} = \frac{4Q}{63}\frac{m}{M}\left(\frac{1}{GM}\right)^{\frac{1}{2}}\frac{a^{6.5}}{R_p^5} \quad .$$

where Q is the so–called damping factor, m is the mass of the companion, and a is the orbital radius. Rasio et al. (1996) show that for 51 Peg the tidal circularization time scale is $\tau_{\mathrm{circ}} \approx 2 \times 10^9$ yr. The 8 extrasolar planets within 0.15 AU may have suffered some tidal circularization, as discussed further by Marcy et al. (1997), Terquem et al (1998), Ford et al. (1998) and Lin et al. (1999). The companions to 55 Cnc and Gliese 86 at a=0.11 AU seem too distant for circularization to be important and yet they have small eccentricities which remains a mystery. If the planetary companions were solid, the circularization time scale would be diminished (Marcy et al. 1997). Conceivably, planets could migrate inward, maintaining their circular orbits without need of tidal effect. Alternatively, planets could be gravitationally scattered inward, and their orbits circularized in a remnant inner gaseous disk, a proposal requiring further work.

Figure 7 shows orbital eccentricities vs. $M \sin i$ which exhibits no obvious trend. This suggests that orbital eccentricity is not correlated with planet mass, within the mass range 0.5–5 $\mathrm{M_{JUP}}$. However, all 5 planets with $M \sin i$ <1.1 $\mathrm{M_{JUP}}$ reside in nearly circular orbits. This correlation may be a selection effect, as the lowest–mass planets are more easily detected close to

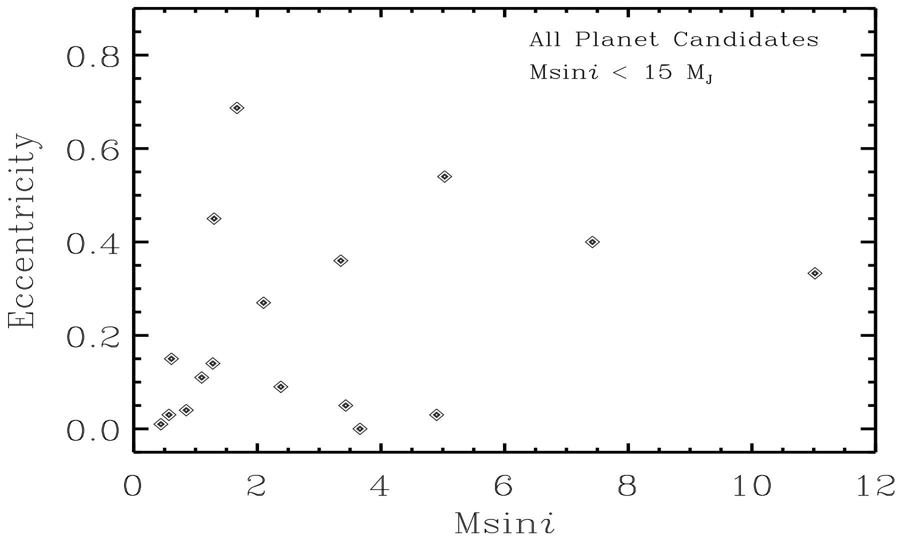

Figure 7. Orbital eccentricity vs $M \sin i$ for all known companions to main sequence in the range $M \sin i$ = 0–15 M_{JUP} . There is no evidence that orbital eccentricities are related to planet mass.

their host stars in order to induce a detectable Doppler reflex signal. These close planets are all subject to tidal circularization. Apparently, whatever mechanism that produces orbital eccentricities is not sensitive to the mass of the planetary companion, within the range 1–5 M_{JUP} .

In contrast to the small orbits that are nearly circular, all 9 planet candidates that have a>0.2 AU reside in eccentric orbits with $e > 0.1$, larger than the eccentricity for both Jupiter (e=0.048) and Saturn (e =0.055) . Figure 8 shows a plot of orbital eccentricities vs. semimajor axis. Apparently, Jupiter–mass companions orbiting from 0.2–2.5 AU (immune to tidal circularization) have large orbital eccentricities. Some mechanism commonly produces eccentric orbits in Jupiter–mass companions that reside from 0.2 – 2.5 AU in main–sequence stars. There is no selection effect operating here, as circular orbits would be easily detected as well. Thus, Jupiter–mass companions generally reside in eccentric orbits within the range a=0.2–2.5 AU, around stars of mass 0.3–1.2 $M_\odot$.

The explanation for eccentricities requires physical processes that are not explicitly included within the context of planet formation. Scattering of orbits by other planets, companion stars, or passing stars in the young star cluster offer mechanisms for producing eccentric orbits (Rasio and Ford 1995, Lin and Ida 1996, Weidenschilling and Marzari 1996, Laughlin and Adams 1999, Holman et al. 1997). General models with such scattering among planets are emerging (Levison et al. 1998). These mechanisms do not explicitly predict small orbits of $<$1 AU, because significant energy must be lost from the original orbits of $\sim$5 AU.

One possibility is that planet–scattering continues to occur during the final era of the remnant gaseous protoplanetary disk. If the disk remains intact within the inner few AU where the original gas density was highest, the disk can serve as the reservoir into which the planet's orbital energy can be deposited, either by dynamical friction or by tidal interaction between planet and disk. In this scenario, scattered planets would reside in eccentric orbits subjecting them to dissipation during periastron passages. Clearly detailed models are required that include both planet scattering and the dissipative effects of a weak inner gaseous disk to determine the resulting planetary orbits.

Are the circular orbits of the giant planets in the Solar System unusual in context of general planetary systems? We have little information about giant planets that orbit beyond 3 AU. We expect such information in the coming years as Doppler programs extend their time baseline. Planets beyond 3 AU may well reside in predominantly circular orbits. A population of giant planets that never suffered significant scattering or migration could comprise these Jupiter analogs. But suddenly, it appears that entropy considerations may favor non–circular orbits for giant planets in general.

Figure 9 shows $M \sin i$ vs. semimajor axis for all 17 planet candidates. Apparently, the distribution of planet masses is not a strong function of semimajor axis from 0.05–2.5 AU for the range of detectable masses, 1–6 M_{JUP} . Some migration models predict that migration is initiated only above some planetary mass threshold (e.g., Trilling et al 1998), the mass at which tidal effects cause significant density perturbations and gaps in the disk. If so, this threshold does not lie from 1–5 M_{JUP} , which appears consistent with migration theory (Lin et al. 1999), but see Ward (1997). We conclude that if orbital migration within a gaseous disk brings the giant plants inward, neither that process nor the halting mechanism seem to depend on planet mass in the observed mass range. It is important to push the detection thresholds to smaller planetary masses, to search for this supposed mass threshold for the onset of migration.

3.5. METALLICITY

The spectra of main sequence stars are routinely analyzed to yield the abundance of the heavy elements relative to hydrogen in the atmosphere. The

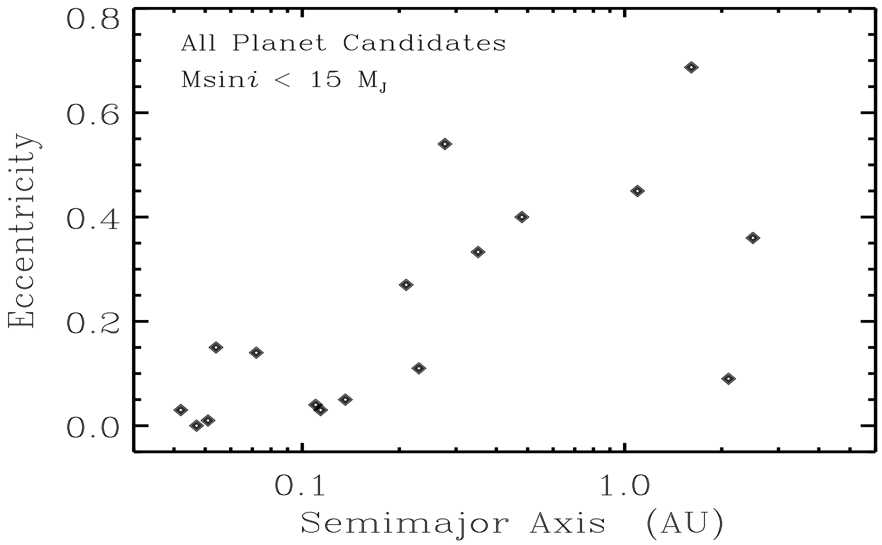

Figure 8. Orbital eccentricity vs semimajor axis for all known companions to main sequence in the range $M \sin i$ = 0–15 $M_{\rm JUP}$. Appranently, planetary companions that are closer than ∼0.2 AU to the star tend to exhibit nearly circular orbits. Remarkably, all 9 Jupiter–mass companions that orbit farther than 0.2 AU reside in non–circular orbits with e >0.1.

resulting metallicities of the planet–bearing stars are shown in Fig. 10 and come from detailed LTE spectroscopic synthesis of high resolution spectra (Gonzalez 1997, Gonzalez 1998, Gonzalez and Vanture 1998, Gonzalez et al. 1998). Figure 10 shows the histogram of metallicities of general G and K–type main sequence stars in the vicinity of the Sun. The planet–bearing stars are shown as tick marks at top, except for a few of the planet–bearing stars for which spectroscopic analysis has not yet been done. Compared to the average of main sequence stars, the planet–bearing stars appear to be metal rich. Figure 10 also includes a tick mark at top–left for the star HD114762 with its companion of $M \sin i$ = 11 $M_{\rm JUP}$. That brown dwarf candidate indeed has low metallicity, [Fe/H] = -0.6 dex, in contrast to the metal rich status of the stars that bear the best planet candidates ($M \sin i <$ 5 $M_{\rm JUP}$).

The most remarkable cases are 55 Cnc and 14 Her, which have metallicities of [Fe/H] = 0.45 ± 0.03 and [Fe/H] = 0.50 ± 0.05, respectively (Gonzalez 1998). Taylor (1996) finds [Fe/H] = 0.38 ± 0.07 for 14 Her. These two stars had been identified as remarkably metal rich prior to the

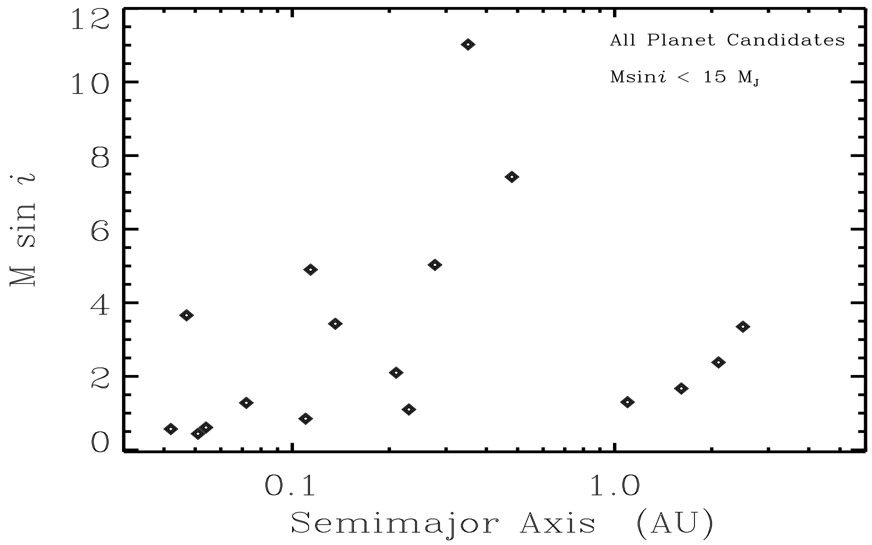

Figure 9. Measured $M \sin i$ vs semimajor axis for all known planet candidates having $M \sin i < 15$ M_{JUP} . No strong correlation is apparent. This suggests that the planet formation process does not place the planets in orbits that depend on their mass. Indeed if a migration process plays a role in transporting planets, that process does not appear to favor companions according to mass within the range 1–5 M_{JUP} , within which detection is robust from 0–2 AU.

planet detection (Taylor 1996), and they comprise two of the seven "Super Metal Rich" stars known in the Solar vicinity (Taylor 1996). The metallicity of HD187123 is also above Solar, [Fe/H] = 0.16. From Fig. 10, the Sun itself is metal rich compared to the field stars nearby.

The correlation between the presence of planets and metal abundance lends support to the standard models of giant–planet formation (Lissauer 1995, Boss 1995, Pollack et al. 1996). In all such models, the heavy elements, as well as water and CO, have condensed into dust. The condensible material coagulates into larger bodies, leading to solid cores which permits the eventual accumulation of gas in Jovian mass. Thus, the observed correlation between the abundance of heavy elements and the presence of planets supports the notion the observed Jupiter–mass companions represent objects similar to the giant planets as modelled.

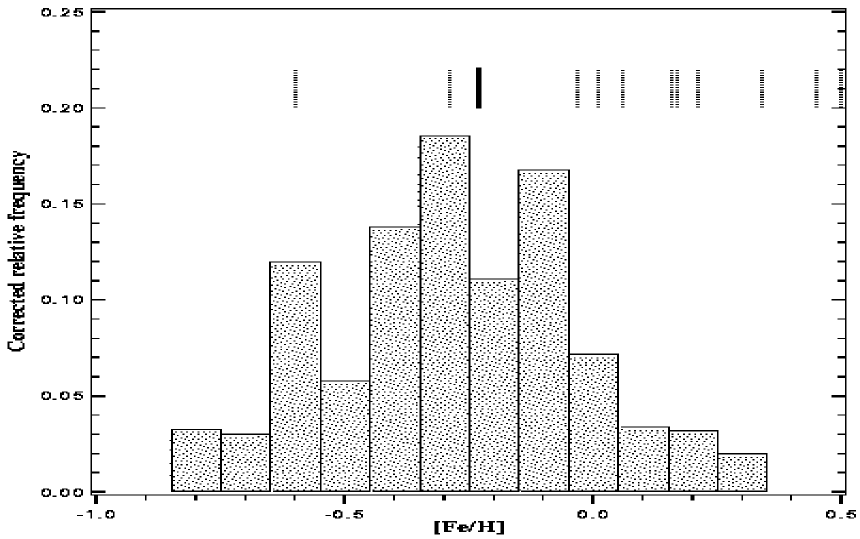

Figure 10. Distribution of metallicities of G and K–type main sequence stars in the Solar neighborhood. The tick marks at the top show the metallicities of stars which have planetary companions, and for which a detailed spectroscopic analysis of the star has been done (Gonzalez et al. 1998). Apparently, planet–bearing stars are rich in heavy elements.

4. Formation of Giant Planets

The basic paradigm for the formation of the Solar System stems from its dynamical architecture, notably the correlated directions of the angular momentum vectors (orbital and rotational) and the nearly coplanar, circular orbits of the planets. There is a radial compositional gradient, from inner heavy element to outer light element constituents. The architecture suggests a model in which the Solar System formed in a Keplerian disk of gas and dust, as described in excellent reviews by Wetherill (1990), Lissauer (1995),Papaloizou and Lin (1995), Lin and Papaloizou (1996), Lin et al. (1999).

The standard Solar–System models often adopt as a benchmark initial condition, the "minimum–mass solar nebula", a 100 AU disk having mass of $\sim$0.02 $M_\odot$(cf Hayashi 1981, Shu et al. 1993, Lin and Papaloizou 1996). This total mass is set by the actual solid material in the nine planets, augmented by a cosmic complement of hydrogen and helium. Disks are indeed found around $\sim$50% of the $\sim$3 Myr-old T Tauri stars (eg, Strom 1994), with measured masses that are similar to the minimum-mass solar nebula (Beckwith and Sargent 1996). Figure 11 shows the measured distribution of disk masses, ranging from 0.005 - 0.2 $M_\odot$. These derived masses may contain systematic errors due to the poorly known gas-to-dust mass ratio (currently taken to be 100), the uncertain dust opacity, and the necessary extrapolation of disk density inward of 100 AU, about which little is known. Some suggest that the disk masses remain uncertain by a factor of $\sim$10, and surface mass densities are similarly uncertain within 20 AU where the giant planets may form. The model disks contain dust and molecular gas with a radial decline in temperature and density, such that ices (mostly water) condense outward of $\sim$4 AU, causing a factor of three rise in the density solids.

The formation of giant planets is thought to have occurred in six stages:

1. Infall of dust grains onto the disk, and their subsequent evaporation and condensation.

2. The formation and growth of solid particles from 1 mm to 1 km sizes, either by gravitational instability (Goldreich & Ward 1972) or by cohesive collisions of grains (Weidenschilling & Cuzzi 1993).

3. The run-away coagulation of planetesimals into prototerrestrial planets (Wetherill 1990).

4. Concurrent accretion of gas and planetesimals onto the terrestrial cores (Pollack et al. 1996).

5. Termination of accretion by gap formation in the disk (Lin et al. 1998, Artymowicz 1998).

6. Clearing of the disk material, by processes not well identified.

5. Future Planet–Detection Techniques

5.1. TRANSITS AND MICROLENSING

Planets may be detected as they transit in front of the disk of a star. The fractional reduction in the light from the star is simply the ratio of the areas of the planet and the star. For a benchmark Jupiter having radius 1 R_J, a Solar-type star will dim by 1% with a duration of order hours, depending on the orbital radius (Hale and Doyle 1994). Such photometry is possible from the ground, made efficient with automated wide–field telescopes that acquire CCD images of thousands of stars simultaneously (Borucki and

Summers 1984). The 1% dimming is easily distinguished from other effects such as starspots, flares, and fluctuations in photospheric granulation which would rarely exceed 1%. Actual transits would cause no change in color, would exhibit a flat–bottomed minimum (with limb-darkened ingress and egress), and would repeat like clock–work.

A transit requires a special geometry, such that

$$\tan i > \frac{a}{R_*}$$

where i is the orbital inclination, a is the planet's semimajor axis and R_* is the star's radius.

For randomly oriented orbital planes, the probability, P, that i will reside between 90 deg (edge–on) and i' is simply: $P(i'\mathrm{to}90^\circ) = \cos i'$. For a population of Jupiters at 0.1 AU (51 Peg-like), 4.7% of them will transit and $\sim$2% of Solar-type stars have such close Jupiters (Marcy and Butler 1998). This implies that one in a thousand Solar-type stars should exhibit transits from close Jupiters. To enrich the stellar sample with edge-on planetary orbits, eclipsing binary stars may be selected. For CM Dra, companions larger than 2.5 Earth radii can be ruled out, for periods less than 60 days (Deeg et al. 1998).

A transit, followed by Doppler measurements of the star, would yield the planet mass directly since $\sin i \approx 1.0$. Transits also yield the radius of the planet and hence its density, which distinguishes gas giants from solid planets. The photometric transit approach should be pursued vigorously.

Transits by Earth-sized planets would dim the star 0.01%. The requisite photometric precision requires a space-borne platform, wide-field camera, and a detector capable of photometric precision of 3:100,000. Such a mission should reveal transits in $\sim$1% of Solar-type stars, if terrestrial planets at $\sim$1 AU are common (Borucki et al. 1996).

The French space mission COROT, to be launched in 2001, is planned to photometrically monitor about 25000 stars and permit the detection of a few dozen extrasolar planets (Schneider 1998).

5.2. ASTROMETRY

The angular wobble of a star in response to its companion is proportional to both planet mass and orbital radius, and inversely proportional to the distance to the star. Reviews of the astrometric approach to planet detection are provided by Gatewood (1987) and Colavita and Shao (1994). As a benchmark, a Jupiter analog orbiting 5 AU from a Solar-type star that is located 10 pc away would produce an astrometric amplitude of 0.5 milliarcsec (mas).

The astrometric technique offers two great prospects: 1. determination of an unambiguous mass and orbital inclination of a planet, 2. detection of sub–Jupiter–mass planets for future astrometric precision below 0.1 mas. An astrometric planet detection provides a secure mass which is not offered by direct detection.

Gatewood (1987) has demonstrated an annually-averaged astrometric precision of 1 mas, which he expects to improve by using the Keck II telescope. Pravdo and Shaklan (1996) have demonstrated a precision of 0.1 mas with direct, short CCD exposures from the Palomar 5-m and Keck telescopes. With the Palomar testbed interferometer, Colavita and Shao (1994) currently achieve precision of 60–70 μas/$\sqrt{hr}$, portending a bright future for next-generation interferometric astrometry. The two Keck telescopes and the European Very Large Telescope Interferometer should yield astrometric precision of 20 μas (Colavita and Shao 1994). A planned NASA space-born astrometric interferometer called the Space Interferometry Mission (SIM) has a goal of 4 μas for global astrometry (Unwin et al 1996; Boden et al. 1996), and perhaps better for planet searches. Due for launch in 2005, SIM astrometry should achieve many–sigma detections of planets having Neptune–like masses ($1/20\,\mathrm{M_{JUP}}$) at 5 AU for stars within 10 pc. A mission lifetime of $\sim$12 years will be required. SIM Interferometric astrometry offers a clear path to statistically valuable ensembles of gas giants through the Neptune–mass regime, to constrain the planetary mass function.

To date, no definitive detection of a planetary companion has been accomplished by the astrometric method. Gatewood (1996) has noted strongly suggestive accelerations in Lal 21185 that may be due to two low–mass orbiting companions, but further data are required to confirm the orbits and masses (Gatewood, 1997, personal communication).

5.3. MICROLENSING

Gravitational microlensing of stars in the Galactic bulge may also reveal the presence of planets in orbit around the intervening lensing Angelobjects. Intensive follow-up photometry of microlensing events by a global telescope network can reveal the short-term perturbations on the standard microlensing light curve caused by an attendant planet (Peale 1997, Griest and Safizadeh 1998). Microlensing is most sensitive to planets at a projected distance from the lensing star of about an Einstein radius, which corresponds to 3-6 AU for a typical galactic bulge microlensing event. The duration of the planetary perturbation on the lightcurve is proportional to $\sqrt{\mathrm{M_P}}$. Microlensing is unique in its ability to detect Earth–mass planets in orbits with semi-major axes of several AU around main sequence stars from the ground (hence inexpensively), and would yield statistics on the occurrence of such planets. Follow–up study of these planets would be difficult owing to their large distance (∼5 kpc), and ambiguities in identifying the lensing object.

5.4. SPACE–BORNE NULLING INTERFEROMETRY

The acquisition of direct images of Earth–like planets will require a space–born interferometer that nulls, by destructive interference, the glaring light from the host star (Beichman 1998, Angel & Woolf 1997). Both the ESA in Europe and NASA in the United States are designing systems that woud have the following general properties. Four telescopes, operating at a temperature of 40K would be separated with a baseline of ∼100m. The telescope would operate at wavelengths of 3–30 μm where thermal emission from planets is maximum. The resulting angular resolution would be ∼0.5 milli-arcsec, depending on wavelength.

Ironically, the direct detection of planets is hindered by the zodiacal dust that both reflects and thermally emits light that competes with the signal from the planet (see, e.g., Beichman 1998, Becklin et al. 1998 and Fajardo-Acosta et al. 1999). These zodiacal dust disks are themselves being used to study the planetary systems in advance of the space–borne interferometry. For example, using ISO observations at 25 μm and 60 μm, Dominick et al. (1998) concluded that 55 Cnc (Table 1) has a disk roughly 60 AU in diameter. In addition, near IR coronographic observations by Trilling and Brown (1998) have resolved the 55 Cnc dust disk yielding its inclination which in turn sets the mass of the planetary companion (1.8 M_{JUP}). They estimate the mass of the disk to be 0.4 Earth-masses, 10× that of the dust in the Solar System. Plausibly this disk is related to the planet(s) around that star (Butler et al. 1997).

Most interestingly, a ring of dust was recently imaged at 850 μm around the nearby K2V star, ϵ Eridani(Jayawardhana et al 1998, Koerner et al. 1998, Greaves et al. 1998), showing that mid–IR and sub–mm imaging may routinely be able to detect dust disks. These images can provide the dust distributions and temperatures in the disks around stars of different ages and metallicities, hopefully conveying the relationship between disk properties and planets.

6. Summary

Precise Doppler measurements of ∼500 main sequence stars have revealed Jupiter–mass companions, yielding the first indications of their distribution of masses, orbital sizes and of eccentricities. Major theoretical questions remain about the origin of these properties. The mass distribution rises sharply at 5 M_{JUP} toward lower masses, indicating a robust formation process. Presumably these Jupiter–mass companions are high mass planets, evidently much more numerous than brown dwarf companions. To date, 17 Doppler companions are known that have $M \sin i < 11$ M_{JUP} . The 5 which orbit closer than 0.1 AU all reside in circular orbits, plausibly induced by tidal interactions with the host star. In contrast, all 9 planet candidates that orbit farther than 0.2 AU reside in eccentric orbits with e >0.1, greater than that of Jupiter (e=0.048). Orbital eccentricity can be induced gravitationally by other orbiting planets, companion stars, passing stars in the dense star-forming cluster, or by the protoplanetary disk, but further theoretical work is needed. The planet–bearing stars are systematically metal–rich, as is the Sun, compared to the Solar neighborhood. This indicates that planet formation depends sensitively on the abundance of heavy elements. The occurrence of planets in the mass decade, 0.5–5 M_{JUP} , within 3 AU is $\sim$5% but that of "brown dwarf" companions in the next higher mass decade, $5 - 50\,M_{JUP}$, is at most 1% within 3 AU. Future planet searches will involve searches for planet transits by the dimming of starlight, giving planet radius. Ground– and space–based astrometry should detect Saturn– and Neptune–mass planets. Gravitational lensing can reveal Earth–mass planets, and future space–borne interferometry is planned to obtain direct images and spectra.

References

Angel R & Woolf N. 1997, ApJ, 475, 373

Artymowicz, P. 1998, On the Formation of Eccentric Superplanets. In Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. L. Martín, and M. R. Zapatero Osorio, pp. 152–161.

Baliunas S. L., Henry G. W., Donahue R. A., Fekel F. C., and Soon W. H. 1997. Properties of Sun-like Stars with Planets: ρ^1 Cancris, τ Bootis, and υ Andromedae. Astrophys. J. Lett. 474:L119–L122.

Basri G, Marcy GW. 1997. in *Star Formation Near and Far (7th Astrophysics Conference)*, ed. by S.Holt & LG Mundy, AIP Conf. Proc., 393:228.

Becklin,E.E., Silverstone,M., Hare,J., Zuckerman, B., Spangler, C. Sargent,A., Goldreich,j P. 1998, "The Universe as seen by ISO", Paris: Abstracts.

Beckwith, S. V. W., and Sargent, A. 1996. Circumstellar disks and the search for neighbouring planetary systems. Nature 383:139–144.

Beichman, C.A. 1998. Terrestrial Planet Finder: The search for life-bearing planets around other stars. SPIE, 3350, 719

Bertelli,G., Bressan, A., Chiosi,C., Fagotto, F., Nasi, E. 1994, A&AS, 106, 275

Black, D.C. 1997, ApJL, 490, L171

Borucki WJ, Summers AL. 1984. *Icarus* 58:121

Boss, A. P. 1995, Science, 267, 360

Boss, A. P. 1997, Science, 276, 1836

Boss, A. P. 1998, ApJ 503, 923

Burrows, A., Sudarsky, D., Sharp, C., Marley, M., Hubbard, W. B., Lunine, J. I., Guillot, T., Saumon, D., Freedman, R. 1997. In Proceedings of the Workshop on Brown Dwarfs and Extrasolar Planets, held in Tenerife, Spain on March 17-20, 1997, ed. R.

Rebolo,E. Martín, M. R. Zapatero Osorio, pp 354-369
Burrows, A., Hubbard, B., Lunine, J., Marley, M., and Saumon,D. 1998, to appear in Protostars and Planets IV, eds. V. Manning, A. Boss. S. Russell.
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Butler, R. P., & Marcy, G. W. 1996, ApJL, 464, L153
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Butler, R. P., Marcy, G. W., Vogt,S.S., Apps, K. 1998, PASP,110,1389
Butler, R. P., Marcy, G. W. & Fischer,D.A. 1999, submitted to ApJ Letters.
Carney, B.W., Latham, D.W., Laird, J.B., and Aguilar, L.A. 1994, AJ, 107, 2240
Cochran, W D., Hatzes, A.P., Hancock, T.J. 1991, ApJL,380, L35
Cochran, W. D., Hatzes, A. P., Butler, R.P., & Marcy, G. M. 1997, ApJ, 483, 457
Cumming, A., Marcy, G.W., and Butler, R.P. 1999, ApJ, in press.
Deeg HJ, Doyle LR, Kozhevnikov VP, Martín EL, Oetiker B, Palaiologou E, Schneider J, Afonso C, Dunham ET, Jenkins JM, Ninkov Z, Stone R, Zakharova PE. 1998, A&A, 338, 479
de la Fuente Marcos, C., de la Fuente Marcos, R. 1997, A&A 326, L21–24.
Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Naif, D., Queloz, D. 1998, A&A, 338L 67
Dominck,C., Laureijs,R.J., Jourdain de Muizon,M. & Habing, H.J., 1998, A&A, 329, L53
Duquennoy, A. and Mayor, M, 1991, A&A, 248, 485
Fajardo-Acosta S.B., Thakur,N., Stencel,R.E., and Backman,D.E. 1999, ApJ, in press
Favata, F., Miccla, G., & Sciortino, S. 1997, A&A, 323, 809
Fischer, D.A., Marcy, G. W., Butler, R.P. Vogt, S.S., and Apps, K. 1999, PASP, 111, 50.
Ford, E. B., Rasio, F. A., & Sills, A. 1998, preprint, submitted to ApJ.
Fuhrmann, K. 1998, A&A, 338, 161
Gatewood GD. 1996. *Bull. Am. Astron. Soc.* 188, #40.11 ABSTRACT
Gonzalez G. 1997. *MNRAS* 285:403
Gonzalez G., and Vanture, A. D. 1998, A&A, submitted.
Gilmore, D. K., Rank, D. M. & Temi, P. 1994, Proc. SPIE Vol. 2198, p. 744-748, Instrumentation in Astronomy VIII, eds. David L. Crawford & Eric R. Craine.
Goldreich P, Ward WR 1973, *Ap.J* 183:1051-61
Goldreich P, Soter S. 1966, *Icarus* 5:375
Goldreich, P. & Tremaine, S. 1980, ApJ, 241, 425
Gonzalez, G. 1998, A&A, 334, 221
Gonzalez, G., Wallerstein, G., Saar,S. 1998, ApJL, in press
Greaves, J.S. et al. 1998, ApJL, in press.
Gray, D. F. 1992, in The Observation and Analysis of Stellar Spectra, 2nd Edition, Cambridge Univ. Press, Cambridge. p431
Halbwachs,J.L., Mayor,M., Udry,S. 1997, in "Brown dwarfs and Extrasolar Planets", Proceedings of a Workshop held in Puerto de la Cruz, Tenerife, Spain, 17-21 March 1997, ASP Conference Series #134, eds. Rafael Rebolo; Eduardo L. Martin; Zapatero Osorio, Maria Rosa, p. 308.
Hale A., Doyle L. R. 1994 The Photometric Method of Extrasolar Planet Detection Revisitied. Astrophys. Space Sci. 212:335–348.
Hale,A. 1995, PASP, 107,22
Hauser H., and Marcy, G. W. 1998. The Orbit of 16 Cygni AB. Pub. Ast. Soc. Pac., submitted.
Hayahsi, C. 1981. Structure of the solar nebula, growth and decay of magnetic fields, and effects of magnetic and turbulent viscosities on the nebula. *Prog. Theor. Phys. Suppl.* 70:35-53.
Heintz, W. 1994, AJ, 108,2338
Henry GW, Baliunas SL, Donahue RA, Soon WH, Saar SH. 1997. *Ap.J.* 474, 503
Holland,W.S., et al. 1998, Nature, 392, 788

Holman, M., Touma, J., and Tremaine, S. 1997. Nature 386, 264
Hatzes, A. P., Cochran, W. D., & Bakker, E. J. 1998, Nature, 391, 15
King JR, Deliyannis CP, Hiltgen DD, Stephens A, Cunha K, Boesgaard AM. 1996. *Astron. J.* 113:1871
Kirkpatrick, J. D. & McCarthy, D. W., Jr. 1994, AJ, 107, 333.
Kurucz, R. L., Furenlid, I., Brault, J., Testerman, L. 1984, National Solar Observatory Atlas No. 1 , (Tucson: NSO)
Jayawardhana,R., Fisher,S., Hartmann,L., Telesco,C., Pina,R. & Fazio,G. 1998, ApJL, 503, 79
Koerner,D.W., Ressler,M.E., WErner,M.W., & Backman,D.E. 1998, ApJL, 503, 83
Latham, D.W., Mazeh, T., Stefanik, R.P., Mayor, M., & Burki, G. 1989, Nature, 339, 38
Laughlin G., and Adams F. C. 1998. Possible Stellar Metallicity Enhancements from the Accretion of Planets. Astrophys. J., 491:L51–L54.
Laughlin, G. and Adams, F.C. 1999, "The Modification of Planetary Orbits in Dense Open Clusters", to appear in ApJ Letters
Levison, H. A., Lissauer J. J., & Duncan, M. J. 1998. AJ, 116, p.1998
Lin DNC. 1986. *The Nebular Origin of the Solar System* in The Solar System: Observations and Interpretation, ed. MG Kivelson. pp.68-69. Prentice-Hall, Englewood Cliffs, New Jersey,
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Nature, 380, 606
Lin DNC & Papaloizou JCB. 1986. *Ap.J.* 309, 846-57
Lin DNC & Papaloizou JCB. 1996. *Annu. Rev. Astron. Astrophys.* 34:703-47.
Lin D. N. C. & Ida S. 1997, ApJ, 477, 781
Lin, D. N. C., Papaloizou, J.C.B., Bryden, G., Ida, S., and Terquem, C. 1999, to appear in Protostars and Planets IV, eds. V.Manning, A.Boss. S.Russell.
Lissauer JJ. 1995. Icarus, 114, 217
Marcy, G. W. & Butler, R. P. 1996, ApJL, 464, L147
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A., & Jernigan, G. 1997, ApJ, 481, 926.
Marcy, G. W., and Butler, R. P. 1998. Detection of Extrasolar Giant Planets. Ann. Rev. Astron. Astrophys. 36, 57.
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., Lissauer, J. J. 1998, ApJ, 505, L147
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., Liu,M.C. 1999, ApJ. to appear Vol. 520, "Two New Candidate Planets in Eccentric Orbits"
Martín EL. 1998 *Lithium in Young Clusters and Pre–Main Sdquence Stars*, to appear in proceedings of the workshop."Cool Stars in Clusters and Associations", held in Palermo, Italy, September 1997, in the *Mem. Soc. Ast. Italy*, ed. G Micela, S Sciortino, R Pallavicini
Max, C. E., Olivier, S. S., Friedman, H. W. An, J., Avicola, K., Beeman, B. V., Bissinger, H. D., Brase, J. M., Erbert, G.V., Gavel, D.T., Kanz, K., Liu, M.C., Macintosh, B., Neeb, K. P., Patience, J., and Waltjen, K. E. 1997, Science 277, 1649.
Mayor, M., Queloz, D. 1995, Nature,378,355
Mayor M, Queloz D, Udry S, Halbwachs J.-L. 1997. in "Astronomical and Biochemical Origins and the Search for Life in the Universe", Proceedings of the 5th International Conference on Bioastronomy , held in Capri, Italy, IAU Colloquium No. 161, ed. C.Cosmovici, S.Bowyer, D.Werthimer . pp.313-30. Editrice Compositori:Italy
Mayor, M., Beuzit, J. L., Mariotti, J. M., Naef, D., Perrier, C., Queloz, D., & Sivan, J. P. 1998, ASP Conf. Ser. (in press), IAU Colloq. 170: Precise Stellar Radial Velocities, ed. J.B. Hearnshaw & C.D. Scarfe, (San Francisco: ASP)
Meyer C., Rabbia, Y., Froeschle, M., Helmer, G., Amieux, G. 1995, A&AS, 110,107
Mazeh, T., Latham,D.W., Stefanik, R. P. 1996, ApJ,466,415
Mazeh T, Krymolowsky Y, Rosenfeld G. 1997. ApJL 477, L103
Mclean, I.S., Macintosh, B.A., Liu, T., Casement, L.S., Figer, D. F., Lacayanga, F., Larson, S., Teplitz, H., Silverstone, M., Becklin, E. E. 1994, Proc. SPIE Vol. 2198,

p. 457-466, Instrumentation in Astronomy VIII, David L. Crawford; Eric R. Craine; Eds.
Ng,Y.K., Bertelli,G. 1998, A&A, 329, 943
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763.
Noyes, R. W., Jha, S., Korzennik, S. G., Krockenberger, M., Nisenson, P., Brown, T. M., Kennelly, E. J., and Horner, S. D. 1997, ApJ, 483, L111
Queloz D., Mayor M., Weber L., Naeff D., Udry S., Santos N., Blecha, A., Burnet, M. and Confino, B. 1999, preprint (on discovery of Gliese86b).
Papaloizou J.C.B. & Lin, D.N.C 1995. *Annu. Rev. Astron. Astrophys.* 33:505.
Perryman, M. A. C., et al. 1997, A&A, 323, L49. The Hipparcos Catalog
Pinsonneault M. 1997. *Ap. J.* 480:303
Pollack,J., Hubickyj,O., Bodenheimer,P., Lissauer, J.J., Podalak,M., Greenzweig,Y., 1996, Icarus, 124, 62
Pravdo, S.H., Angelini, L., Drake, S.A., Stern, R. A., White, N.E. 1996, New Ast,1,171
Pravdo S. H., and Shaklan, S. B. 1996. Astrometric Detection of Extrasolar Planets: Results of a Feasibility Study with the Palomar 5 Meter Telescope. Astrophys. J. 465:264–277.
Rasio, F. A., & Ford,E. B. 1996, Science, 274, 954
Rasio, F. A., Tout,C.A., Lubow, S.H., & Livio, M. 1996, ApJ, 470, 1187
Saar, S. H. & Donahue R.A. 1997, ApJ, 485, 319.
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 403, L153.
Shirts, P. & Marcy, G. W. 1998, preprint to be submitted to PASP.
Shu FH, Najita J, Ruden SP, Lizano S. 1994. *Ap.J.* 429:797-807
Soderblom DR, Jones BF, Balachandran S, Stauffer JR, Duncan DK, Fedele SB, Hudon JD. 1993. *Astron. J.* 106:1059
Strom SE. 1994. in: *Cool Stars, Stellar Systems, and the Sun, Eighth Cambridge Workshop* p. 211. San Francisco: Astronomical Soc. Pacific
Szokoly, G. P., Subbarao, M. U., Connally, A.J., and Mobasher, B. 1998, ApJ,492,452
Taylor,B. 1996, ApJS, 102, 105.
Terquem, C., Papaloizou, J.C.B.,Nelson, R.P., Lin, D. N. C., 1998, ApJ, 502, 788
Trilling D., Benz W., Guillot T., Lunine J. I., Hubbard W. B., Burrows A., 1998, ApJ, 500, 428
Trilling D., Brown, R. preprint submitted to Nature
Unwin S, Boden A, Shao M. 1996, *Bull. Am. Ast.Soc.* 189, 121.02 ABSTRACT
Van de Kamp P. 1963. *Astrometric Study of Barnard's Star from Plates Taken with the 24-inch Sproul Refractor, Astron. J.*, 68:515-521.
Vogt, S. S. et al. 1994, Proc. Soc. Photo-Opt. Instr. Eng., 2198, 362
Walker, G.A.H., Walker, A.R., Irwin, A.W., Larson, A.M., Yang, S.L.S., Richardson, D.C. 1995. *Icarus* 116:359
Ward, W. R. 1997, ApJ, 482, L211
Weidenschilling S, Cuzzi. JJ. 1993. In *Protostars and Planets III*, ed. E Levy, J Lunine, M Matthews. pp.1031-60. Tucson: University of Arizona Press,
Weidenschilling, S. J. & Marzari, F. 1996, Nature, 384, 619
Wetherill GW. 1990. *Ann. Rev. Earth Planet Sci.* 18:205-56
Wolszczan A & Frail DA 1992. *Nature* 355:145
Wolszczan A 1998, to appear in *Reviews in Modern Physics*