PART VII

Extrasolar Planets and Brown Dwarfs

The mass distribution of substellar companions exhibits a steep rise for masses below 5 M_{Jup}. Thus, the 14 companions having $M \sin i = 0.5–5\ M_{Jup}$ are considered the best candidate planets around main-sequence stars. The occurrence of such planets within 3 AU is ∼4%, but two-thirds of them orbit within just 0.3 AU. This "pileup" of planets near stars suggests that inward orbital migration occurred after formation. The planet candidates orbiting within 0.1 AU have nearly circular orbits, but all nine of those orbiting outside 0.2 AU have $e > 0.1$, i.e., greater than that of Jupiter, $e_{Jup} = 0.048$. Thus, eccentric orbits predominate for Jupiter-mass companions from 0.2 to 2.5 AU and may arise from gravitational interactions with other planets, stars, or the protoplanetary disk. The planet-bearing stars are systematically metal-rich, as is the Sun, compared to the solar neighborhood. The occurrence of "brown dwarf" companions in the next higher mass decade, 5–50 M_{Jup}, is at most 1% within 3 AU, based on surveys of ∼600 stars. Thus, brown dwarfs represent a minimum in the mass function of companions, between the masses of stars and of planets.

I. INTRODUCTION

Our Sun is a very common and ordinary star. There is really nothing to distinguish it from a myriad of other similar stars in this region of the Galaxy. Yet, the Sun possesses a marvelous system of nine diverse planets. This has led us to believe that the formation of planetary systems should be a natural, common result of the process of star formation. We expect that a significant fraction of solar-type stars should have some type of planetary system in orbit around them. The discovery by the Hubble Space Telescope (HST) of disks of dust around many stars in the Orion nebulae certainly reinforces that feeling. The quest to discover and explore these extrasolar planetary systems has proven to be a difficult and elusive task that has occupied astronomers for decades. The early phases of the search for substellar companions are chronicled by van de Kamp (1977, 1982, 1986).

However, much to the surprise of everybody, the first confirmed detection of an extrasolar planetary system was not found around a "normal" main-sequence star like the Sun but rather around a millisecond pulsar, PSR 1257+12 (Wolszczan and Frail 1992; Wolszczan 1994). It was not until three years later, with the discovery of the companion to 51 Pegasi in the astonishing 4.23-day orbit (Mayor and Queloz 1995), that the first planetary-mass companion was found in orbit around a solar-type star. Further, the detection and spectrum of the brown dwarf, Gliese 229b, portends the wealth of information obtainable by future direct images of extrasolar planets, which we hope will be made possible with space-borne interferometers (Oppenheimer et al. 1998; Beichman 1998).

In this chapter, we will discuss the quest for planets around stars like the Sun, for it is these systems that shed light on the physics of star formation and allow us to test the elaborate paradigm that has developed for the process of planetary system formation.

II. TECHNIQUES

A. Radial Velocities

In a typical high-dispersion optical spectrometer, a Doppler shift of one pixel corresponds to 2000 m s^{-1}, which is much larger than the wobble velocity of the Sun, 13 m s^{-1}, due to Jupiter. A secure detection of a Jupiter analog requires that Doppler shifts be measured with a precision of $\sim \frac{1}{1000}$ pixel or, correspondingly, that wavelengths be measured with a precision of 1:10^8.

Radial velocity precision of $\sim$10 m s^{-1} is accomplished by three basic approaches. Several groups use a glass container filled with iodine gas, which is placed at the entrance of the spectrometer. The resulting iodine absorption lines are superimposed on the stellar spectrum to provide the wavelength calibration (Marcy and Butler 1992; Cochran and Hatzes 1994; Noyes et al. 1997). The iodine lines also reveal the asymmetries in the instrumental profile that induce spurious Doppler shifts. The iodine permits removal of such instrumental effects. The iodine cells were developed as a safer and more versatile alternative to the HF gas absorption cell used by Campbell et al. (1988).

In the second approach, two fiber optic cables feed the stellar light and the calibration emission source (typically thorium) into the spectrometer (Brown et al. 1994; Mayor and Queloz 1995). The fiber approach carries two advantages. The entire spectrum can be used (not just the region containing iodine lines), and the stellar spectrum is not contaminated by iodine lines. One disadvantage is that the optical path of the calibration light is not identical to that of the starlight, thus rendering the approach vulnerable to zonal optical aberrations.

A third method is to use a tunable Fabry-Perot etalon as the velocity metric (McMillan et al. 1990, 1994). A cross-dispersed echelle spectrograph spatially separates the Fabry-Perot interference maxima on a charge-coupled device (CCD) detector. Small Doppler shifts of a star will then become evident through changes in the intensities of those Fabry-Perot orders falling on the steep slopes of stellar absorption lines.

B. 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 and (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/hr$^{-1/2}$, 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-borne astrometric interferometer called the *Space Interferometry Mission* (SIM) has a goal of 4 μas for global astrometry (Unwin et al 1999; Boden et al. 1996), and perhaps better for planet searches. Due for launch in 2006, SIM should achieve many-σ detections of planets having Neptune-like masses ($\frac{1}{20}$ M_{Jup}) at 5 AU for stars within 10 pc. A mission lifetime of $\sim$12 years will be required. 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 Lalande 21185 that may be due to two low-mass orbiting companions, but further data are required to confirm the orbits and masses (G. D. Gatewood, personal communication, 1997).

C. 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_{Jup}, 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 clockwork.

A transit requires a special geometry, such that

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

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

For randomly oriented orbital planes, the probability P that i will reside between 90° (edge-on) and i' is simply: $P(i'$ to $90°) = \cos i'$. For a population of Jupiters at 0.1 AU (51 Peg-like), 4.7% of them will transit, and ~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 Draconis, 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, because $\sin i \approx 1.0$. 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 ~1% of solar-type stars if terrestrial planets at ~1 AU are common (Borucki et al. 1996).

The French space mission COROT, to be launched in 2001, is planned to monitor about 25,000 stars photometrically and permit the detection of a few dozen extrasolar planets (Schneider et al. 1998).

Gravitational microlensing of stars in the galactic bulge may also reveal the presence of planets in orbit around the intervening lensing objects. 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 light curve is proportional to $\sqrt{M_P}$. Microlensing is unique in its ability to detect Earth-mass planets in orbits with semimajor 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 ($\sim$5 kpc) and ambiguities in identifying the lensing object.

III. PLANETARY RESULTS TO DATE

Several previous Doppler surveys for planets and brown dwarfs done from 1980 to 1990 foreshadowed and constrained the results to come later. Doppler surveys of $\sim$200 K- and M-type dwarfs at a precision of $\sim$250 m s^{-1} (Marcy and Benitz 1989; Tokovinin 1992) would have revealed 5–80-M_J companions within 3 AU. No such substellar companions were found. Another Doppler survey of 570 G and K dwarfs, done with a precision of 300 m s^{-1}, revealed 10 brown dwarf candidates (Duquennoy and Mayor 1991; Mayor et al. 1997). With similar precision, Latham et al. (1989) identified another one having $M \sin i = 11\ M_{Jup}$, though Cochran et al. (1991) have suggested that $\sin i$ may be small. Studies of the distribution of $\sin i$ show that some of these companions are likely to be simply H-burning stars, not brown dwarfs (Mazeh et al. 1992; Marcy and Butler 1995). Mayor et al. (1998*a*) have indeed shown that almost all have $M > 0.075\ M_\odot$, based on Hipparcos satellite astrometry that constrains $\sin i$ (see section IV.C). Murdoch et al. (1993) pushed "classical" radial velocity techniques to a very impressive precision limit of 55 m s^{-1} in their survey of 29 solar-type stars for low-mass companions. In a survey that pioneered the field of high-precision radial velocity work, Walker et al. (1995) monitored 21 late F, G, and K dwarfs for 12 yr at a precision of 13 m s^{-1}. No companions were found above a threshold of $2M_{Jup}$ within 5 AU.

These Doppler surveys impose a firm upper limit on the occurrence of brown dwarf and planetary companions. At most 1% of 0.3–1.2 $M_\odot$ stars harbor a brown dwarf (10–80 M_{Jup}) within 3 AU. Similarly, at most 5% have giant planets above 2 M_{Jup} within 3 AU. By 1994, it had become clear that companions having more than twice Jupiter's mass are rare within 5 AU.

Several teams responded to this absence of detections by monitoring Doppler shifts of larger samples of F, G, K, and M dwarfs at higher precision ($\sim$10 m s^{-1}). Leading surveys were carried out by McMillan et al. (1993), Cochran et al. (1997), Mayor and Queloz (1995), Noyes et al. (1997), and Marcy and Butler (1998). Mayor and Queloz (1995) have now monitored 140 main-sequence stars for 4 yr, and Cochran and Hatzes (1994) have monitored 33 stars for 11 yr. Marcy and Butler (1997) have monitored 107 F, G, K, and M dwarfs for 11 yr, and Noyes et al. (1997) have searched ∼100 additional solar-type dwarfs and subgiants for ∼3 yr. In all cases, the stellar selection avoided binaries with separations less than 2 arcsec (typically ∼20 AU), to avoid double spectra and to reject stars for which detectable planets could not persist dynamically. A total of ∼300 individual stars were surveyed.

Starting with the detection of the companion to 51 Peg (Mayor and Queloz 1995; Marcy et al. 1997), the Doppler surveys above have now revealed 17 companions that have $M \sin i < 11\ M_{Jup}$ (see Table I). Figures 1a and 1b show the Doppler measurements for the eight planet candidates known just prior to the *Protostars and Planets IV* meeting in June 1998, reviewed by Marcy and Butler (1998). Figures 2 and 3 show the Doppler measurements for two planets announced at that meeting, namely around Gliese 876 (M4 V; Marcy et al. 1998, Delfosse et al. 1998) and 14 Herculis (K0 V; Mayor et al. 1998*d*). Gliese 876 is an M4 dwarf, suggesting that planets are common around stars from 1.3 to 0.3 $M_\odot$. The planet around 14 Her has a period of at least 4.5 yr, implying that $\alpha > 2.5$ AU, the largest orbit yet found for a planet candidate. Figure 4 shows the Doppler results for HD 187123, which has a planet with the shortest period to date, $P = 3.09$ d and $M \sin i = 0.59\ M_{Jup}$ (Butler et al. 1998). A summary of all planet candidates known as of January 1999 is provided by Marcy et al. (1999). Table II shows the stellar characteristics of those planet-bearing stars for which careful spectroscopic synthesis has been carried out (Gonzalez 1998*a,b*).

The 5-M_{Jup} benchmark may represent a physically meaningful upper limit to planetary masses, because the companion mass distribution rises discontinuously at that mass (Fig. 6). Thus, companions with $M \sin i < 5\ M_{Jup}$ represent the best extrasolar planet candidates. Table I shows the orbital characteristics, P, a, K, e, and minimum masses of these planet candidates, along with the few that have $M \sin i = 5$–$11\ M_{Jup}$. Here, P is orbital period, a is semimajor axis, K is the velocity semi-amplitude, and e is orbital eccentricity. We shall refer to these 17 companions as the extrasolar planet candidates. Planets may also be distinguished from brown dwarfs by their inability to ignite deuterium as brown dwarfs do (Burrows et al. 1997).

The orbital periods of the 17 extrasolar planets range from 3.1 d to 4.5 yr, corresponding to semimajor axes of 0.04 to 2.5 AU. However, 11 of the 17 planets have $a < 0.3$ AU. This "piling-up" of planets near their host stars appears to be a real effect, although enhanced by the selection effect that favors detection of small orbits (see section IV.C).

Upsilon (υ) Andromedae, after subtraction of the clear wobble that is caused by the planet with $P = 4.6$ d, exhibits velocity residuals with two

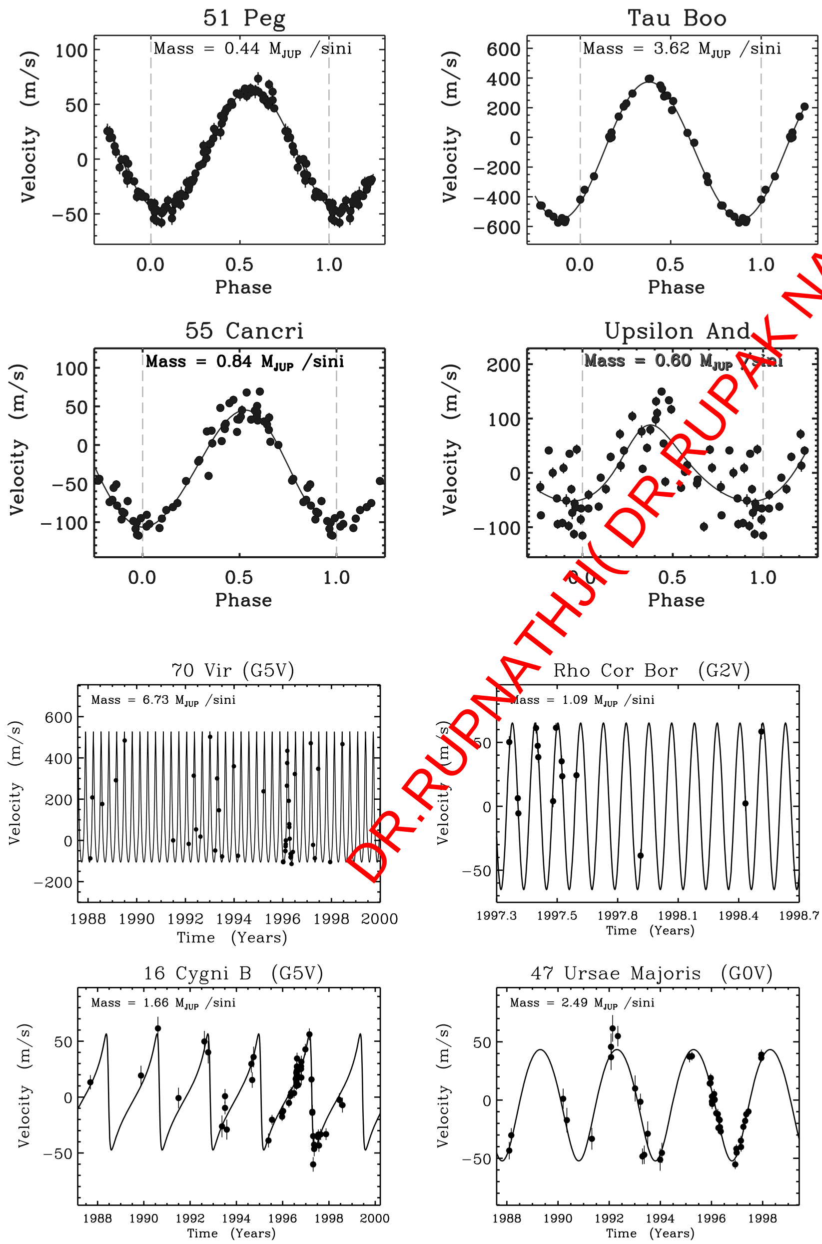

Figure 1. Doppler data for the first eight planet candidates that have $M \sin i < 5$ M$_{\rm Jup}$, including the marginal 70 Virginis, with $M \sin i = 6.8$ M$_{\rm Jup}$. (a) The short–period planets, having $P < 15$ d. All have nearly circular orbits, possibly induced by tidal effects. b) The long–period planets, having $P = 39$ d–3 yr. Two have eccentric orbits and two have $e < 0.15$. Tidal effects should play no role for these.

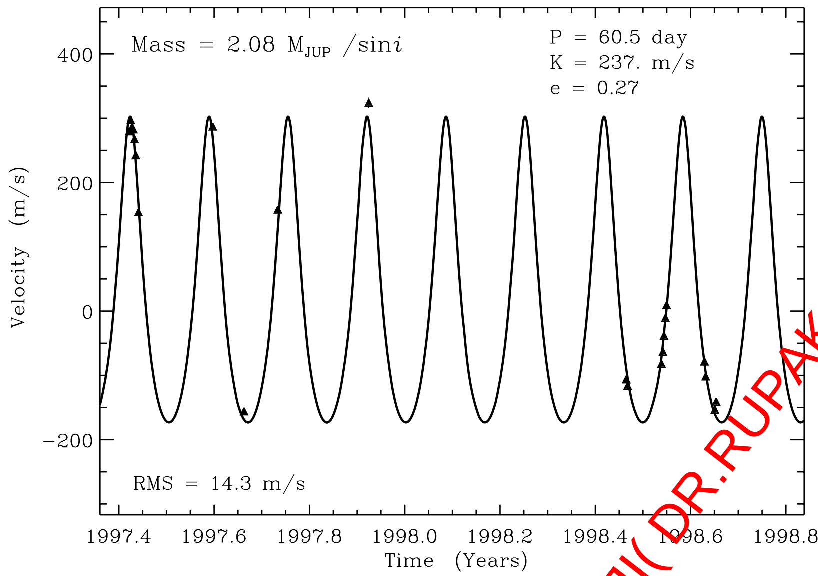

Figure 2. The Doppler data for Gliese 876 from the Keck telescope, displayed at the *Protostars and Planets* IV meeting. The implied planet has $P = 61$ d, $a = 0.20$ AU, and $e = 0.27$. Gliese 876 is spectral type M4 V, with mass = 0.32 $M_\odot$, suggesting that planets may be common around low-mass stars.

additional periods of 240 ± 10 and 1300 ± 30 d. The raw velocities are well fitted by three companions orbiting at 0.05, 0.83, and 2.5 AU, with minimum ($M \sin i$) masses of 0.75, 1.9, and 4.4 Jupiter masses, respectively (Butler et al. 1999). This multiple-planet system appears to be the first ever found around a main-sequence star outside the solar system.

IV. INTERPRETATION OF VELOCITY RESULTS

A. Orbital Inclinations and sin *i*

The actual masses of the planetary candidates remain unknown pending determination of the orbital inclination i. Upper limits to i come from Hipparcos astrometry in a few cases (Perryman et al. 1996). For example, the lack of astrometric wobble of 47 UMa imposes an upper mass limit of 7 M_{Jup} for that planet (Table I).

Nonetheless, a hypothetical population of 10–80-M_{Jup} brown dwarfs could serve, in principle, as the reservoir from which nearly face-on orbits would masquerade as planets. In an ensemble of randomly oriented orbital planes, the fraction whose normal vector points toward us within angle i (double cone) is $P(i) = 1 - \cos i$. For example, $\sin i$ lies between 0 and 0.1 in only 1:200 random orbits. In comparison, the ~300 stars surveyed probably contain only ~3 brown dwarf companions, too small a brown dwarf reservoir to expect any having $\sin i < 0.1$. Thus, it is un-

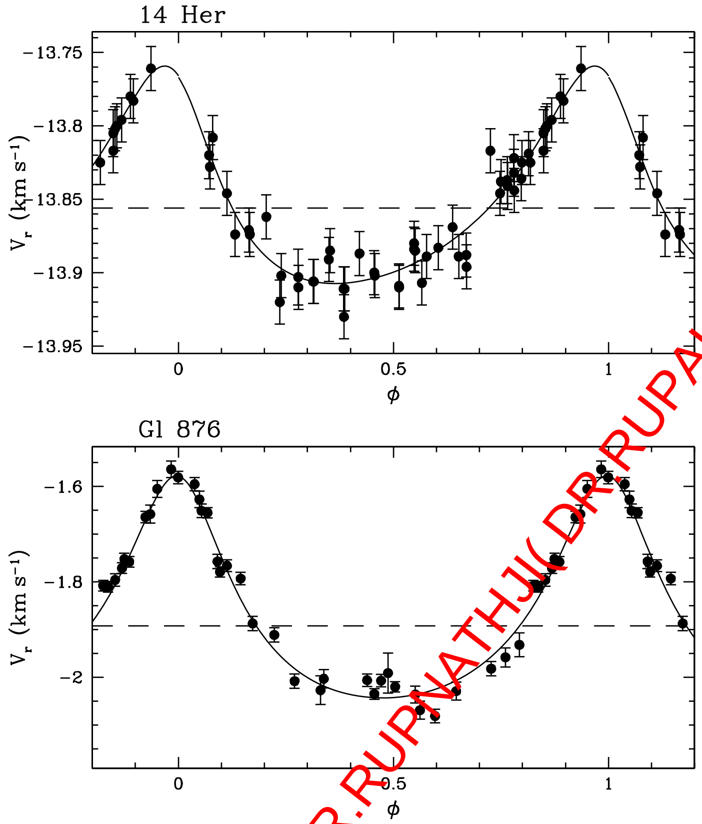

Figure 3. The two new planets announced at the IAU 170 and *Protostars and Planets IV* meetings, based on Haute-Provence Observatory measurements. (a) Phased Doppler data for 14 Her (K0 V). The planet has P >1630 d, a >2.5 AU, and $e \approx 0.34$. This is the longest-period extrasolar planet yet found, and more measurements are needed to determine the period more precisely. (b) Phased Doppler data for Gl 876.

likely that any of the candidate planets have masses 10 times greater than their $M \sin i$.

It is tempting to adopt an "expectation" value of $\sin i$, given by the mathematical mean of its distribution: $\langle \sin i \rangle = \pi/4$. However, selection effects render this approach dangerous, because the most easily detectable companions reside in nearly "edge-on" orbits ($i \approx 90°$), which would produce the highest velocity amplitudes. Thus, edge-on orbital inclinations are favored, implying that the actual planet mass resides close to $M \sin i$. Put differently, the bias toward detecting edge-on orbits implies that the largest values of the $M \sin i$ distribution (near 5 M_{Jup}) represent the maximum planetary masses themselves.

For the shortest-period planets at least, we could expect collinear spin axes for the stellar rotation and planet orbital motion. From a precise

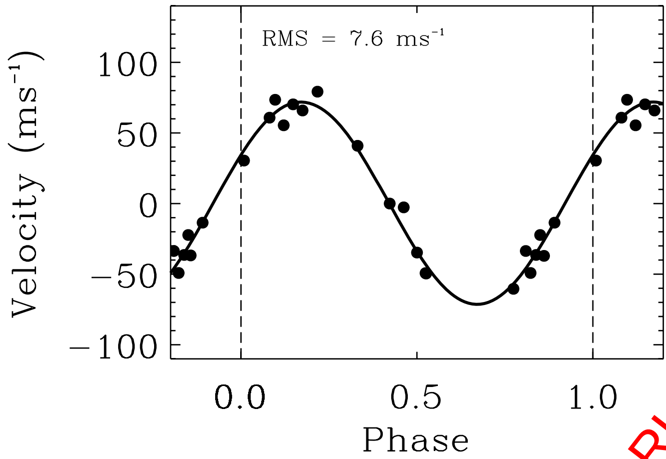

Figure 4. The phased Doppler data for HD 187123 (G3 V) from the Keck 1 Observatory. The planet has $M \sin i = 0.57\,M_{Jup}$, $P = 3.09$ d, $a = 0.042$ AU, and $e \approx 0.00$. This is the smallest planetary orbit known. Tidal effects presumably circularized the orbit, if not primordial.

TABLE I

Orbits of Extrasolar Planet Candidates[a]

Star	P (d)	a (AU)	K (m s^{-1})	e	$m \sin i$ (M_{Jup})	Companion Mass[b] (M_{Jup})
HD 187123	3.097	0.042	83.	0.03	0.57	
τBoo	3.3125	0.047	468.	0.00	3.66	$5.9^{+43.9}_{-1.8}$
51 Peg	4.231	0.051	56.0	0.01	0.44	0.49 ± 0.03
υ And	4.62	0.054	71.9	0.15	0.61	$0.76^{+0.19}_{-0.09}$
HD 217107	7.11	0.072	141	0.14	1.28	
55 Cnc	14.65	0.11	75.9	0.04	0.85	>0.66
Gliese 86	15.84	0.11	379.	0.04	3.6	
HD 195019	18.3	0.14	269	0.05	3.43	
Gliese 876	61	0.21	239	0.27	2.1	
ρ CrB	39.6	0.23	67.	0.11	1.1	$2.9^{+13.6}_{-1.3}$
HD 168443	57.9	0.28	330	0.54	5.04	
HD 114762	84.0	0.35	618	0.33	11.0	
70 Vir	116.5	0.47	316	0.40	7.4	>9.4
HD 210277	437	1.10	41.5	0.45	1.28	
16 Cyg B	799	1.6	50.3	0.687	1.67	$2.0^{+1.1}_{-0.3}$
47 UMa	1092	2.1	47.3	0.10	2.45	$3.4^{+3.1}_{-1.1}$
14 Her	1620	2.5	75.	0.36	3.3	

[a] All planet candidates as of January 1, 1999.
[b] Mass estimates from Gonzalez (1998*a,b*).

TABLE II
Parent Stars of Planet Candidates[a]

Star	T_{eff} (K)	log g (cgs)	ξ_t (km s^{-1})	[Fe/H]	M_V
υ And	6250 ± 100	4.30 ± 0.10	1.40 ± 0.10	0.17 ± 0.08	3.45 ± 0.03
τ Boo	6600 ± 100	4.50 ± 0.15	1.60 ± 0.10	0.34 ± 0.09	3.53 ± 0.03
55ρ^1 Cnc	5250 ± 70	4.40 ± 0.17	0.80 ± 0.09	0.45 ± 0.03	5.47 ± 0.03
ρ CrB	5750 ± 75	4.10 ± 0.05	1.20 ± 0.10	−0.29 ± 0.06	4.18 ± 0.03
16 Cyg B	5700 ± 75	4.35 ± 0.05	1.00 ± 0.10	0.06 ± 0.06	4.60 ± 0.04
51 Peg	5750 ± 75	4.40 ± 0.10	1.00 ± 0.10	0.21 ± 0.06	4.52 ± 0.04
47 UMa	5800 ± 75	4.25 ± 0.05	1.00 ± 0.10	0.01 ± 0.06	4.29 ± 0.03
70 Vir	5500 ± 75	3.90 ± 0.05	1.00 ± 0.01	−0.03 ± 0.06	3.68 ± 0.04
14 Her	5300 ± 90	4.27 ± 0.16	0.80 ± 0.12	0.49 ± 0.05	5.31 ± 0.03
Gliese 876	–	–	–	–	11.80 ± 0.03
HD 187123	5830 ± 40	4.40 ± 0.07	1.00 ± 0.08	0.16 ± 0.03	4.43 ± 0.03
HD 114762	5950 ± 75	4.45 ± 0.05	1.00 ± 0.10	−0.60 ± 0.06	4.23 ± 0.13

[a] Planet-bearing stars for which detailed atmospheric analysis has been done (Gonzalez 1998*a,b*)

measurement of stellar radius and $V \sin i$, we can derive an orbital inclination estimate and then estimate the mass of the planet. Different values have been proposed by Gonzalez (1998*a,b*) and Fuhrmann et al. (1998), and the Gonzalez mass estimates are listed in Table I.

B. Detection Efficiency and Selection Effects

The Doppler approach is most sensitive to planets that impart the largest reflex velocity to the host star. The velocity semiamplitude, K, is given by

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

where m_p is the mass of the unseen companion and $M_\star$ is the stellar mass. The period can be replaced by the semimajor axis with Kepler's third law.

In practice the detectability of reflex velocities depends on both the Doppler errors and the density of sampling in orbital phase. As a rule of thumb, with about 20–30 data points well spread in phase, one can reliably detect a velocity wobble if $K > 4\sigma$, where σ represents the velocity uncertainty in a given measurement.

This detectability criterion is apparent empirically in Fig. 5, which shows the detectability in the two-parameter space of semimajor axis and companion mass ($M \sin i$). Two curves show the locus of points of constant velocity amplitude for 10 and 40 m s^{-1}, assuming circular orbits. For reference, a Jupiter mass orbiting at 1 AU induces a reflex velocity of 28 m s^{-1} in a 1-$M_\odot$ star. Figure 5 also shows many of the detected planet candidates to date, as dots. These dots clearly show that amplitudes over 40 m s^{-1} have been required for detection, owing to the Doppler precision of 10 m s^{-1} that characterized the Doppler surveys during the past 10 yr.

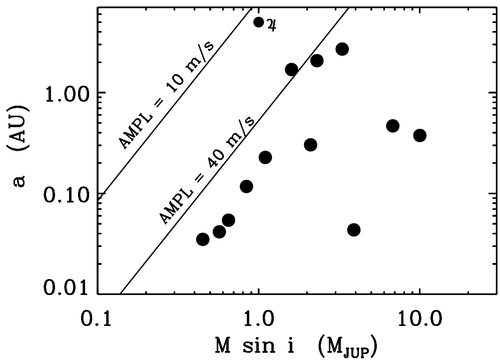

Figure 5. Detectability of companions by the induced reflex velocity, as a function of the orbital radius and companion mass (for circular orbits). The lines represent constant reflex velocities of 10 and 40 m s^{-1}. Planetary companions are shown as dots, including Jupiter. Past precision of 10 m s^{-1} enabled detection of amplitudes above 40 m s^{-1}, suggesting that 3 m s^{-1} (annual average) is required to detect a true Jupiter at 5 AU.

Figure 5 suggests that the detection of true Jupiter analogs at 5 AU will require a precision of under 10 m s^{-1}.

C. Planetary Masses, Semimajor Axes, and Eccentricities

Three specific major surveys can be examined to elucidate the mass distribution of substellar companions from 0 to 70 M_{Jup} within 5 AU. These three surveys include the modest-precision (300 m s^{-1}) survey of ~600 G and K dwarfs by Mayor, Duquennoy, and Udry (Duquennoy and Mayor 1991; Halbwachs et al. 1998). The other two are high-precision Doppler surveys of Mayor and Queloz (1995) and Marcy and Butler (1998), which surveyed 140 and 107 G and K stars respectively. The first survey of modest precision revealed 10 "brown dwarf" candidates, characterized by $M \sin i = 15$–60 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 $M_\odot$.

The M $\sin i$ values for the surviving substellar candidates are shown in Fig. 6, drawn from all three surveys mentioned above. This histogram shows eight companions in the mass bin from 0–5 M_{Jup} (i.e., those planet candidates from Table I that came from only these three surveys). From 5 to 10 M_{Jup}, there is only one companion (70 Vir b). The remaining mass range from 10 to 70 M_{Jup} contains only four companions. Thus, there is

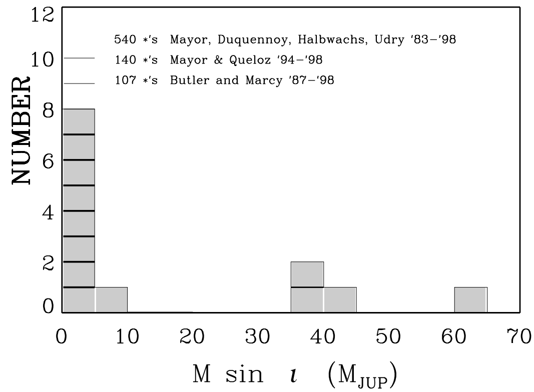

Figure 6. Histogram of M sin i for all companions known around solar-type stars, in the domain 0–70 M_{Jup}, within 5 AU, drawn from two large surveys of Mayor et al. (1997) and Marcy and Butler (1998). Companions for which Hipparcos astrometry has shown that $M > 70$ M_{Jup} have been removed. The tallest peak resides at the lowest masses (0–5 M_{Jup}), and signals a jump in the mass function. Selection effects favor detection of the more massive companions; conversely, companions having $M < 5$ M_{Jup} suffer incompleteness, suggesting that the current peak underestimates their relative occurrence. The brown dwarf regime is sparsely populated, indicating that at most 1% of G and K stars have brown dwarfs within 5 AU. In logarithmic mass intervals, the planetary regime is still more populated than the brown dwarf regime.

a remarkable spike in the mass function for masses from 0 to 5 M_{Jup}, in contrast to the "desert" of brown dwarfs of higher mass. Indeed, those four 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.

Thus, nature manufactures companions having masses below 5 M_{Jup} more prodigiously than it does companions from 5 to 70 M_{Jup} within 3 AU. 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 function at 5 M_{Jup} permits a taxonomic segregation in the populations on either side. A common nomenclature is found in the terms "planet" and "brown dwarf" for the two species. Clearly, the formation processes for both types await further work, notably to determine kinship with the planets in our solar system.

Eleven of the extrasolar planets detected to date reside in close orbits, with $a < 0.3$ AU. The full histogram of semimajor axes of the extrasolar planets is shown in Fig. 7. Such small orbits were not predicted by theory (Lissauer 1995; Boss 1995). The surprisingly small orbits stand in apparent contrast to the prediction that the giant planets formed first from ice grains, which exist only beyond ~3 AU. Such grain growth provides the supposed requisite solid core around which gas could accrete. In section V.A we describe current migration models to explain these close orbits.

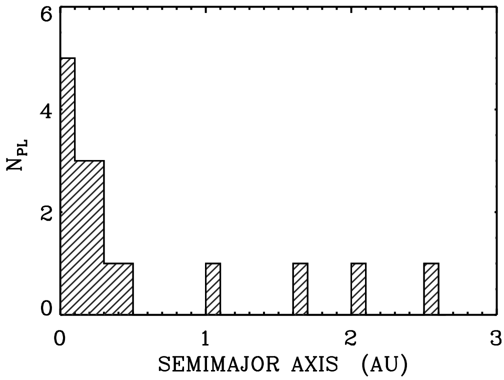

Figure 7. Histogram of semimajor axes of extrasolar planets to date. The preponderance of planets within 0.3 AU appears to be a real effect, because detectability of Jupiters is complete within 1.5 AU, as evidenced by the detections of three companions beyond 1.5 AU. Orbital migration inward may explain this piling-up of planets.

Nonetheless, it appears that giant planets in general reside systematically close to the host star, despite the obvious selection effect that enhances detectability for the closest planets. For example, giant planets that reside 0.5–1.5 AU from their stars would impart a reflex velocity of 25–40 m s^{-1}, which is clearly detectable with current precision. Indeed, Marcy and Butler (1998) have achieved precision better than 5 m s^{-1} for 60 chromospherically quiet stars from Lick Observatory during the past 3 yr. None exhibit planetary-mass companions with a semimajor axis between 0.5 and 1.5 AU. Thus, the distribution of planetary semimajor axes contains an apparent maximum within 0.1 AU, in terms of dN/da.

The eccentricities of the extrasolar planet candidates range from 0.00 to 0.68, and nine out of 17 have an eccentricity above that of Jupiter, $e = 0.05$ (see Table I). Remarkably, all nine planet candidates that orbit farther than 0.2 AU from their host stars (and hence are immune to tidal circularization) reside in noncircular orbits. The large orbital eccentricities have been interpreted by some to imply that they are simply "brown dwarfs" (Mazeh et al. 1996; Black 1997), defined as objects that form "as stars do." If so, brown dwarfs extend from 75 M_{Jup} toward arbitrarily lower masses, with only theoretical ideas (such as opacity-limited cloud fragmentation, e.g., Boss 1988) remaining to constrain the lowest mass at which "star formation" can occur. Instead, it is more likely that these Jupiter-mass companions form in protostellar disks and acquire eccentricities by gravitational perturbations.

It is interesting to compare the distributions of orbital eccentricities for companions to solar-type stars when the mass rises from the domain of giant planets to that of stellar secondaries. Figure 8 illustrates the distri-

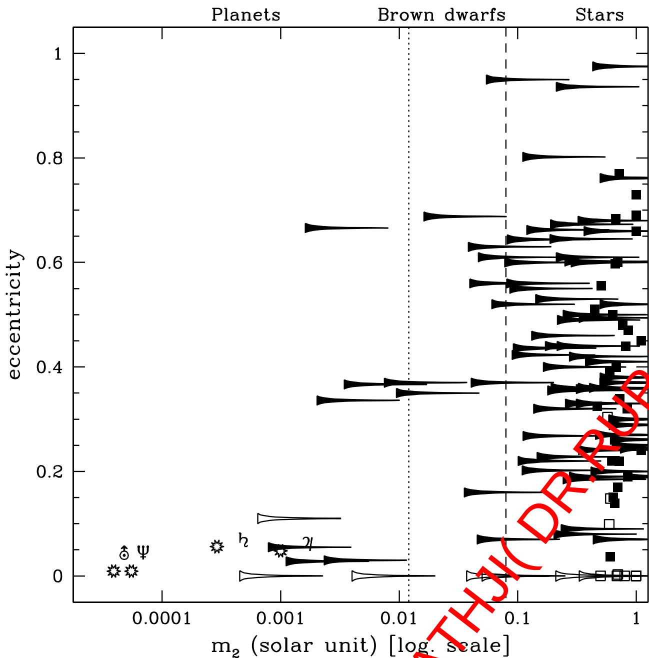

Figure 8. The eccentricity-mass ($M_{\odot}$) distribution of companions to solar-type stars. Starlike symbols are used to identify the four giant planets of our solar system. Binaries among G and K dwarfs of the solar neighborhood are plotted with squares if their actual masses are known and with wedges otherwise; the width of a wedge at a given mass is proportional to the probability of having such a mass due to the $\sin i$ distribution. Empty symbols indicate probable circularization by tidal interaction with the central star.

butions (e, $\log m_2$) (updated version of Fig. 9 of Mayor et al. 1997). The physical interpretation of the diagram is discussed in section V.B.

Although brown dwarfs presumably form at masses approaching 10 M_{Jup} and perhaps lower, the observed mass function (dN/dM) exhibits a dramatic rise at 5 M_{Jup} (Fig. 6). The peak of the mass function distribution is still more impressive if we consider an enlarged domain of mass (up to 0.6 $M_{\odot}$) for the companions to solar-type stars (Fig. 9). One may adopt the view that a continuum of formation processes, from 75 to 1 M_{Jup}, somehow yields a sharp increase in the mass distribution near 5 M_{Jup}. Alternatively, one may interpret the discontinuous increase in the mass function for $M < 5$ M_{Jup} (Fig. 6) as an indication that new formation processes are operating. We adopt this latter view. Thus while the orbital eccentricities of the sub-5 M_{Jup} objects seem similar to those of the more massive stellar companions, the significance of the jump in the mass function at 5 M_{Jup} cannot be ignored. Whether identifications of the members residing on either side of 5 M_{Jup} as "planets" and "brown dwarfs" proves valuable will require additional detections and more sophisticated theory.

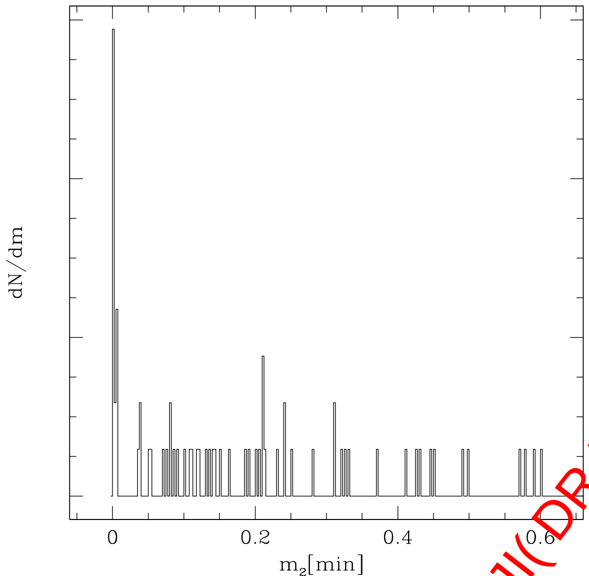

Figure 9. The distribution of companion masses ($M_\odot$) to solar-type stars within the solar vicinity (G–K V). The number of Jupiter-mass detections has been weighted according to the relative sizes of the observed samples.

D. Metallicity

The metallicities of the planet-bearing stars are shown in Fig. 10 and come from detailed local thermodynamic equilibrium (LTE) spectroscopic synthesis of high-resolution spectra (Gonzalez 1997, 1998*a,b,* Gonzalez and Vanture 1998). The histogram of metallicities [Fe/H] = log([Fe]/[H])/([Fe]/[H])$_\odot$ of both field and planet-bearing stars are shown (the latter as tick marks at top), except for that of Gliese 876, for which a spectral synthesis is yet to be done. The field star measurements come from Table 12 of Gonzalez (1998*b).* Compared to stars in the surrounding galactic field, the planet-bearing stars appear to be metal rich. Figure 10 also includes a tick mark at top for the star HD 114762 with its companion of $M \sin i = 11$ M_{Jup}, a brown dwarf candidate. That star indeed has low metallicity, [Fe/H] = −0.6, in contrast to the metal-rich stars that harbor the best planet candidates, which have $M \sin i < 5$ M_{Jup}.

The correlation between the presence of planets and high stellar metallicity represents a remarkable (and the only) astrophysical tie between their existence and independent stellar properties. The correlation thus lends support to the existence of the planets but alternatively could signify some stellar pathology that produces spurious Keplerian Doppler shifts, a prospect that seems unlikely.

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

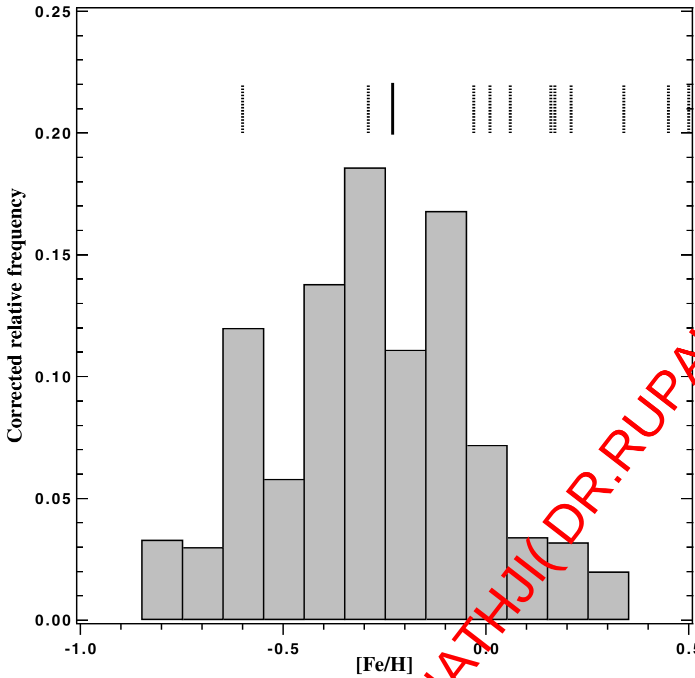

Figure 10. The histogram of [Fe/H] for field stars (shaded) and the planet-bearing stars (upper tick marks) presented by Gonzalez (1998*a,b*). The planet-bearing stars are systematically metal rich. The [Fe/H] for HD 114762 is represented by the tick mark at far upper left, indicating that star to be significantly metal poor relative to the planet-bearing stars. Indeed, its companion has $M \sin i = 10\ M_{Jup}$, suggesting brown dwarf status. The heavy tick mark at top shows the mean [Fe/H] of the nearby star distribution. The solar metallicity, [Fe/H] = 0, is clearly metal rich compared to the field.

(Gonzalez 1998*a,b*). Taylor (1996) finds [Fe/H] $= 0.38 \pm 0.07$ for 14 Her. These two stars had been identified as remarkably metal rich prior to the planet detection (Taylor 1996), and they are two of the seven "Super Metal Rich" stars known in the solar vicinity (Taylor 1996). The metallicity of HD 187123 is also above solar, [Fe/H] $= 0.16$. From Fig. 10, the Sun itself is metal rich compared to the field stars nearby.

It is not clear what the causal relationship is between planets and high metallicity, if indeed the correlation is real. High metallicity may enhance growth rates of rocky cores. Alternatively, giant planets may pollute the host star with metals (Laughlin and Adams 1998).

E. Fraction of Stars with Planets

The detections of planetary companions by different surveys provides estimates of the fraction of stars that harbor them. The Lick Observatory of 107 F, G, K, and M stars revealed 6 companions having $M \sin i < 7\ M_{Jup}$ (Marcy and Butler 1998). Among these, 70 Vir with its large $M \sin i$ =

6.8 M_{Jup} may be considered a planet or brown dwarf. The Lick survey has lasted for 11 yr, providing sensitivity to companions having semimajor axes as large as 5 AU. The historical precision of $\sim$10 m s^{-1} implies that companions having masses greater than 2 M_{Jup} would have been detected at 5 AU, but companions having masses of $\sim$1 M_{Jup} are detectable only within 1 AU. Roughly, the Lick survey implies that within 5 AU, $\sim$5% of solar-type stars harbor companions having masses 0.5–5 M_{Jup}.

The Haute Provence Observatory project (Mayor and Queloz 1995; Mayor et al. 1998*b)* has surveyed 140 F, G, and K dwarfs for 4 yr. It has revealed two planetary companions (51 Peg and 14 Her) and was sensitive to companions having $M \sin i \sim 1$ M_{Jup} at 1 AU. Ironically, although carried out with shorter duration than the Lick survey, this project has discovered the longest period yet found, 14 Her, with $a \approx 2.5$ AU. Thus from this survey, the occurrence of Jupiters within 2.5 AU appears to be $\sim$2%.

The surveys by Walker et al. (1995) and by Cochran and Hatzes (1994) add constraints on the planetary occurrence rate that are consistent with those from Lick and Haute Provence. An approximate average of these surveys, with no weighting, yields an occurrence of Jupiter-mass companions within 3 AU of 4%.

V. ASTROPHYSICAL IMPLICATIONS

A. Orbital Migration

Migration of protoplanets in disks had been predicted prior to the detection of the extrasolar planets by Goldreich and Tremaine (1980), Ward (1981), Lin and Papaloizou (1986), Ward and Hourigan (1989), and Artymowicz (1993); see the chapters by Lin et al. and by Ward and Hahn, this volume. There appear to be two possible modes of angular momentum loss:

1. Small giant planet cores of a few Earth masses, which cannot clear a gap in the protostellar disk, lose angular momentum via interactions with the Lindblad resonances induced in the disk (Artymowicz 1993; Ward 1997). The timescale for orbital decay in a nominal disk may be as short as $\sim 3\times10^5$ yr.
2. The second migration mode occurs for protoplanets with mass $M >$ $\sim$0.1 M_{Jup}, which clear a gap in the disk. The clearing of the gap may curtail the growth of the planet, thereby setting the upper limit to the planet mass function (Artymowicz and Lubow 1996; Lin et al., this volume). Gravitational tidal torques between the planet and disk material at the inner and outer gap edges transfer angular momentum outward and thus force the planet to flow inward along with the viscous disk material toward the star (Ward 1997; Lin and Papaloizou 1995; Trilling et al. 1998). The time for material at 5 AU to drain into a T Tauri star appears to be $\sim 1\times10^6$ yr, from measured values of the mass accretion rate and the disk mass (Valenti et al. 1993; Hartmann et al. 1997; Beckwith and Sargent 1996).

Migration of Jupiters implies that they may form and spiral into the star within 1×10^6 yr. Successive Jupiters may form, each meeting the same fate (Lin 1986). Finally, the viscous timescale is matched by the remaining lifetime of the disk, at which point the last Jupiter survives, left at some intermediate point in its travel. Inward migration implies that giant planets will be found at a range of orbital distances, 0–20 AU from the host star. Their final distribution may not be uniform, because the migration speed, *dr/dt,* depends on the surface density profile of the disk, for a given *dM/dt.*

The deposited Jupiters might be statistically located with a probability distribution that is proportional to the timescale for inward migration, which in turn is proportional to the local surface mass density, $\sigma(r)$ for a fixed mass accretion rate. If $\sigma(r)$ increases inward for typical T Tauri disks, then Jupiters may be found preferentially close to the star.

Lin et al. (1996) suggested that the 51 Peg-type planets (now including υ And, τ Boo, and HD 187123) might have originally formed at $\sim$5 AU according to the conventional planet formation paradigm (Boss 1995; Lissauer 1995). These planets then may have suffered inward orbital migration as described above. The inward migration may be stopped at about 0.05 AU, either by tidal interactions with the spin of the star or by the clearing of the inner disk by the stellar magnetosphere (Lin et al. 1996). Trilling et al. (1998) consider the possibility that Roche lobe overflow by the planet can halt the migration, though the mechanism is difficult to implement.

B. Origin of Orbital Eccentricities

Four mechanisms appear capable of generating eccentricities as added processes to the standard paradigm of planet formation. Protoplanets excite spiral density waves in the protoplanetary disk, which can gravitationally perturb the planet, pumping the eccentricity to modest values (Artymowicz 1998; Lubow and Artymowicz, this volume). It remains to be seen how high the eccentricities can be augmented by this process.

Multiple giant planets can mutually perturb each other, causing orbit crossings and large gravitational scatterings (Weidenschilling and Marzari 1996; Rasio and Ford 1996; Lin and Ida 1997). Arbitrarily high eccentricities can result (see the chapter by Lin et al., this volume). These scattering models predict that Doppler measurements should eventually reveal additional eccentric companions. None has yet been found. Further, planetesimals and other planets may gently perturb the orbits of giant planets over timescales of 10 Myr during runaway accretion (Lissauer et al. 1995) or over timescales of the “heavy bombardment” period ($\sim$100 Myr) as computed by Levison et al. (1998).

Eccentric giant planets could be formed in open star clusters as a result of purely dynamical processes. Up to 50% of giant planets around G stars in open clusters can develop high eccentricities due to multibody gravitational interactions, as shown by de la Fuente Marcos and de la Fuente Marcos (1997) and by Laughlin and Adams (1999).

Finally, a stellar companion (such as 16 Cyg A) can gravitationally pump the eccentricity of a planet, even for ratios of orbital separation (star-star vs. star-planet) as great as 1000 (Holman et al. 1997; Mazeh et al. 1997; Cochran et al. 1997). Indeed, the eccentric orbit of 16 Cyg A and B brings them within 1000 AU and possibly within 200 AU, making stellar perturbations plausible (Hauser and Marcy 1998; Romanenko 1994).

C. Formation in Clusters

Our standard paradigm for star and planet formation assumes that the system forms in isolation; once the collapse of the protostar begins, it does not interact with its surroundings in any way. However, it is quite likely that most (if not all) stars form in clusters, where the stellar density is much higher than in the field where we find the older stars (Lada et al. 1991). A simple comparison of the sizes of protostellar disks (100–1000 AU) with the mean stellar separation in protoclusters (5000–10,000 AU) suggests that star-disk and disk-disk encounters must be important. Kroupa (1995*a,b,c)* explored the dynamical evolution of star-forming clusters and concluded that the observed frequency and properties of field binary stars is consistent with all stars having formed in clusters of binary systems. Gravitational encounters between a disk and a nearby star (Boffin et al. 1998) or between two disks (Watkins et al. 1998*a,b)* can drastically alter the evolution of the disk from the theoretically idealized case of a completely isolated disk. At the densities of most current star-forming regions, most protostars will undergo at least one significant interaction with a neighboring star before its protostellar disk is dissipated. Star-disk encounters are unlikely to lead to capture, but coplanar disk-disk encounters can result in the formation of multiple-star systems. More important for the problem of planet formation, however, is what happens to the disk material during such encounters. Star-disk encounters can truncate the disk, strip newly formed planets from the system, or introduce tilts and twists of up to 30° in the disk (Boffin et al. 1998). In disk-disk encounters, disk material can be swept into a shock layer, which can fragment to produce new condensations (Watkins et al. 1998*a,b).* Clearly, the types of planetary systems formed under these conditions may differ drastically from our current idealized models.

D. Miscellaneous

The Doppler detection of planets is subject to the alternative interpretation that the stars are pulsating rather than undergoing reflex motion (Gray 1997; Gray and Hatzes 1997). Under the assumption of radial pulsation, the time integral of the velocity during $\frac{1}{4}$ period indicates the net physical displacement of the photosphere. For most stars listed in Table I, this hypothetical displacement due to pulsation is more than 1% $R_{\odot}$. Such large changes in stellar radius (at optical depth unity) should cause photometric variations over 1% unless nature conspires to hide the oscillations with temperature changes that cancel the radius changes. Barring that, the millimagnitude-level photometric constancy of the stars in Table I (Baliunas et al. 1997; Henry et al. 1997) renders radial oscillations unlikely. Nonradial sectoral-mode oscillations can produce effective shifts of spectral lines while causing small photometric variability (Gray and Hatzes 1997). In addition, the observed stellar line profile may be slightly distorted by starlight that is reflected at particular orbital phases by a close-in planetary companion (Charbonneau et al. 1998). The line profiles of τ Boo and of 51 Peg exhibit constant shape when observed at high spectral resolution and high signal-to-noise ratios, which also argues against oscillations (Brown et al. 1998*a,b;* Gray 1998; Hatzes et al. 1998*a,b;* Hatzes and Cochran 1998). However, one must beware of the possibility of oscillations that might maintain line shape while displacing the entire line. Further, extraordinarily new physics is always possible, so pulsations can never be ruled out. However, more work is required to securely understand stellar pulsation and surface velocity fields in general.

VI. CONCLUSIONS

Jovian-mass companions have been found around other solar-type stars. Radial velocity surveys have now reached the level of precision at which such planet candidates can be found routinely. Other detection techniques should reach this point in the near future. The mass distribution of substellar companion objects reveals the tail of the stellar mass function in the 10–70-M_{Jup} regime, and a significant excess of objects at masses less than 5 M_{Jup}. This indicates that two different physical processes operate. The star-formation process forms the more massive group of substellar companions that are true brown dwarfs. The objects with masses of a few Jupiter masses that orbit within a few AU are most probably formed in the protoplanetary disk and thus are planets according to most standard definitions. It is not yet clear whether there is some overlap in the 10–70-M_{Jup} mass ranges of brown dwarfs and of planets; that answer will require better statistics on the mass ranges of both types of objects.

Remarkably, all nine planet candidates that orbit beyond 0.2 AU reside in eccentric orbits, unlike the circular orbits of the solar system gas giants. Such eccentric orbits predominate among Jupiter-mass companions from 0.2–2.5 AU and may stem from perturbations imposed by the other planets, passing stars, or by the protoplanetary disk.

None of the systems found so far resembles ours, with a massive planet at a distance from the central star at which ice would have condensed in the protostellar disk. While this is partly a result of detection sensitivity (close-in planets give a larger Doppler signal), there is a significant tendency for planets to be found within 0.3 AU of the star. Formation of objects in these close-in orbits is extremely difficult but not necessarily impossible.

Early dynamical evolution of the system provides an explanation for the observed distribution of planetary semimajor axes. Tidal torques between the newly formed planet and the remnant disk can cause an inward migration of the gas giant planet from the 3+ AU region, where it can be formed easily, to the inner regions, where such planets reside today. The piling-up of planets near 0.05 AU is quite remarkable and suggests that there is some efficient mechanism to stop this inward migration of planets just before they plunge into the star.

Stars that have detected planets in orbit around them appear to be slightly metal-rich compared to the general population of disk solar-type stars. This can be understood within our current understanding of the planet formation process. The core of a jovian planet is thought to grow by collisional growth and accretion of solid planetesimals in the disk. The speed of this process should scale roughly as the square of the metallicity, because collisional rates proceed as density squared. Gas giant planets should form more rapidly around metal-rich stars. If the planet forms while there is still a viscous disk, it will migrate inward. It is quite possible that some planets may not magically stop their inward migration at 0.05 AU and may spiral all of the way into the star. This would only slightly pollute the stellar convective zone with metal-rich material.

The true test of our paradigm of solar system formation requires the characterization of many systems of multiple planets. The three planets around υ Andromedae offer the first indication of possibly extensive diversity among such systems.

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