A New Era in Bioastronomy
ASP Conference Series, Vol. 213, 2000
G. Lemarchand, K. Meech (eds.)

Extrasolar Planets Around Main Sequence Stars

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Abstract. Planetary systems have emerged as a new class of astronomical objects, studied by a remarkable array of new observations. Doppler observations of stars have revealed 35 planets having masses predominantly less than $\sim 8\,\mathrm{M_{JUP}}$, with increasing numbers of planets having the lowest detectable masses, $\sim 1\,\mathrm{M_{SAT}}$. Most surprisingly, all 21 planets that orbit beyond 0.2 AU reside in quite elliptical (rather than circular) orbits, providing the first suggestion that our Solar System may be unusual compared to other planetary systems. A system of three planets has been found around the main sequence star Upsilon Andromedae, the first "solar system" outside our own. The three planets are kept dynamically stable by a resonance between the outer two planets as revealed by the aligned axes of their ellipses. One extrasolar planet has a known diameter, measured by the amount of dimming of its host star during a transit, which indicates that the planet is gaseous rather than solid.

Infrared images of young and old stars reveal surrounding dust disks consisting of unusually large particles with sizes $10\,\mu$m. The disks often have gaps, rings, and holes similar to the structure in the Zodiacal dust and Kuiper Belt of our Solar System. These disk features may be caused by gravitational shepherding of the dust by planetary bodies. Indeed the dust is regenerated by collisions among comets and asteroids whose presence is indirectly inferred from the longevity of the dust.

1. Introduction

The evidence for Jupiter-sized planets around other stars is now overwhelming, and the handful of interpretations to the contrary have vanished (Marcy & Butler

1999; Marcy *et al.* 2000). The Doppler periodicities of stars are consistent with gravitational tugging by orbiting planets. The term "planets" is now deemed appropriate for these Jupiter-mass companions, because a full system of three planets has been found around Upsilon Andromedae (see below). The planets discovered to date are probably gaseous, as determined from the measurement of the (low) density in one case, HD209458b. The 35 known extrasolar planets exhibit masses and orbital ellipticities that bear directly on their formation and subsequent gravitational history. Comparison of our Solar System with others has become possible.

Equally impressive are the disks of dust now routinely detected around nearby stars. The dust is found around both young stars and old stars. The masses and sub–structure of these disks give unique information about the evolution and survival of the dust, and about its relationship to the planets.

2. Observed Properties of Extrasolar Planets

2.1. Masses and Orbits

As of 2000 March, Doppler surveys of ~500 main sequence stars have revealed 35 planets having roughly Jupiter–mass (cf., Marcy *et al.* 2000). The term "planet" is reserved, by definition, for objects that form "similarly to those in our Solar System". Such formation implies that multiple planets should form in one disk, which in turn implies a criterion for planet status: that several be found around a single star. However, the physical processes that produce planets in disks remain the subject of theoretical work (cf., Lin *et al.* 2000).

The properties of planets around stars must be combined with theory to infer the as–yet-undetectable processes within protoplanetary disks and planetary systems. To date, Doppler searches are sensitive to planets (and brown dwarfs) within 3 AU which have masses greater than $\sim 1\ \mathrm{M_{SAT}}$. Figure 1 shows the histogram of companion mass estimates drawn from all Doppler surveys of FGKM dwarfs (Butler & Marcy 1997; Mayor *et al.* 1997; Noyes *et al.* 1997; Cochran *et al.* 1997; Halbwachs *et al.* 2000; Marcy *et al.* 2000; Vogt *et al.* 2000; Henry *et al.* 2000; Charbonneau *et al.* 2000). The distribution of $M \sin i$ reveals a paucity from 8–20 $\mathrm{M_{JUP}}$, but an increase from 8 $\mathrm{M_{JUP}}$ toward the lowest detectable masses, 0.2 $\mathrm{M_{JUP}}$, at which detection becomes poor. Within 3 AU, there is apparently a paucity of "brown dwarf" companions, relative to planets, with an occurrence of less than 0.5%. Nonetheless, free brown dwarfs are abundant in the Galaxy (Kirkpatrick *et al.* 1999). Planets rarely form with masses above $\sim 8\,\mathrm{M_{JUP}}$, but the mass distribution rises toward lower masses, consistent with, $\mathrm{d}N/\mathrm{d}M \propto M^{-1}$.

The stars that harbor extrasolar planets seem to have higher abundances of the heavy elements, compared to the Sun, by a factor of ~2 (Gonzalez *et al.* 1999). This suggestion must be verified, but seems strong at this time, though cause is not fully understood. If planets form by coagulation of dust, protoplanetary disks rich in silicon and iron might well condense larger dust grains and grow more rapidly into planets.

A list of all strong planet candidates is given in Table 1. The table contains an update of the orbital properties and $M \sin i$ values, current as of March 2000. These updates include current velocity measurements from Lick and Keck observatories (many unpublished) along with modern values of the stellar masses (which set $M \sin i$) based on distances from the Hipparcos satellite data. These stellar masses mostly come from our calibration of ubvy photometry giving metalicity and mass from stellar evolution calculations, and some masses come from Prieto and Lambert (1999) which does not account for metalicity.

Table 1 includes all planets listed in Marcy *et al.* (2000), along with several recent detections (Vogt *et al.* 2000; Korzennik *et al.* 2000).
The histogram of planetary masses as revealed from their $M \sin i$ is shown in Fig. 1. The mass distribution rises from about 10 M_{JUP} toward the lowest detectable masses of 1 M_{SAT}.

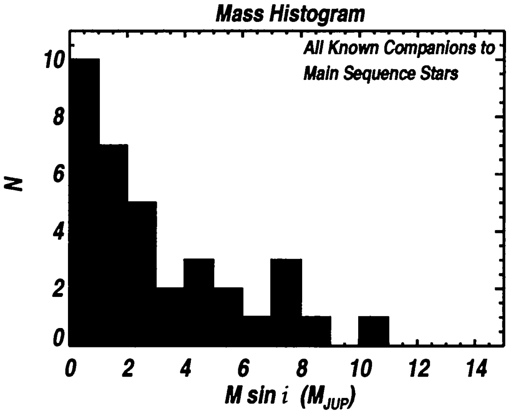

Figure 1. Histogram of $M \sin i$ for all companions known between 0-15 M_{JUP}.

The extrasolar planets that orbit within 0.1 AU reside in nearly circular orbits, perhaps enforced by tidal circularization (cf., Lin *et al.* 2000). But all 21 planets that orbit farther than 0.2 AU from their star reside in non–circular orbits having $e > 0.1$. These planets move in orbits that are more elliptical than the orbits of Venus, Mars, Earth, Jupiter, and Saturn. The large orbital eccentricities may result from gravitational perturbations imposed by planetesimals, the disk, or passing stars (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Lin & Ida 1997; Levison *et al.* 1998; Artymowicz 1993; Holman *et al.* 1997; Laughlin & Adams 1998).

None of the models that produce orbital eccentricity has emerged as definitive. Nonetheless, the plethora of mechanisms that can disturb circular orbits, rendering them eccentric, suggests that the majority of planetary systems may indeed suffer such perturbations. Our Solar System may have started with initial conditions, i.e., planet masses and orbital separations, that rendered the planets immune to mutual gravitational disturbances. In the future, planets will be found that orbit 4–6 AU from the host star, allowing a direct comparison of those orbital shapes with our Jupiter.

2.2. A Transiting Planet

Velocity measurements from the Keck telescope reveal a sinusoidal periodicity in the F8 main sequence star, HD 209458, having a velocity amplitude of 81 m $s^{-1}$and a period of 3.523 d. From Kepler's third law, the orbital radius is

Table 1. Extrasolar Planets: Updated as of March 2000

Star	$M_{\rm Star}$ ($M_\odot$)	P (d)	K (m/s)	ecc.	Msin i ($M_{\rm JUP}$)	a (AU)
HD 46375	0.96	3.023	35.0	0.00	0.24	0.040
HD 187123	1.06	3.097	72.0	0.01	0.54	0.042
Tau Boo	1.30	3.313	474.0	0.02	4.14	0.047
HD 75289	1.22	3.508	54.0	0.00	0.46	0.048
HD 209458	1.05	3.524	82.0	0.02	0.63	0.046
51 Peg	1.06	4.231	55.2	0.01	0.46	0.052
Ups And b	1.30	4.617	70.2	0.02	0.68	0.059
HD 217107	0.98	7.130	139.7	0.14	1.29	0.072
HD 130322	0.89	10.720	115.0	0.05	1.15	0.092
55 Cnc	1.03	14.656	75.8	0.03	0.93	0.118
GJ 86	0.86	15.800	379.0	0.04	4.23	0.117
HD 195019	1.02	18.200	271.0	0.01	3.55	0.136
HD192263	0.79	24.35	68.2	0.22	0.81	0.152
Rho CrB	0.95	39.81	61.3	0.07	0.99	0.224
HD 168443	1.10	58.10	469.0	0.52	8.13	0.303
GJ 876	0.32	60.90	235.0	0.24	2.07	0.207
HD 16141	1.03	75.20	12.7	0.43	0.24	0.352
HD 114762	0.82	84.03	615.0	0.33	10.96	0.351
70 Vir	1.10	116.68	316.2	0.40	7.42	0.482
HD 1237	0.96	133.80	164.0	0.51	3.45	0.505
HD 37124	0.91	154.80	48.0	0.31	1.13	0.547
Ups And c	1.30	241.30	58.0	0.24	2.05	0.828
HD 134987	1.05	260.0	50.2	0.24	1.58	0.810
HD 12661	1.07	264.5	90.6	0.33	2.83	0.825
HD 89744	1.43	265.0	256.8	0.70	7.35	0.910
Iota Hor	1.19	320.0	80.0	0.16	2.98	0.970
HD 177830	1.17	391.0	34.0	0.40	1.24	1.103
HD 210277	0.99	436.6	39.1	0.45	1.29	1.123
HD 222582	1.00	576.0	179.6	0.71	5.18	1.355
16 Cyg B	1.01	796.7	50.0	0.68	1.68	1.687
HD 10697	1.10	1074.0	114.0	0.11	6.08	2.119
47 UMa	1.03	1084.0	50.9	0.13	2.60	2.086
Ups And d	1.30	1308.5	70.4	0.31	4.29	2.555
14 Her	1.06	1700.	95.9	0.37	5.44	2.842

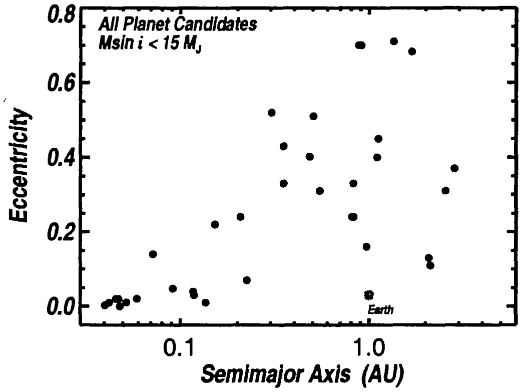

Figure 2. Orbital Eccentricity vs Semimajor Axis for extrasolar planets. All planets orbiting farther than 0.2 AU reside in non-circular orbits.

0.046 AU and the minimum mass ($M \sin i$) is 0.62 $M_{\rm JUP}$ (Henry *et al.* 2000). Photometry by two groups independently revealed a decrease in the brightness of the star by 1.7% at the predicted time of transit by the companion based on the velocities (Charbonneau *et al.* 2000; Henry *et al.* 2000). This is the only extrasolar planet that has transited its star.

The fractional dimming of the star equals the fractional area of the star that is blocked by the planet, thereby giving the planet's radius, $1.4 \pm 0.15\, R_{\rm JUP}$. This bloated radius compared to that of Jupiter is consistent with models of irradiated Jupiter–mass planets (Guillot *et al.* 1996; Saumon *et al.* 1996; Burrows *et al.* 1998). The transit constrains $\sin i$ to be 1.00, leading to an actual mass of 0.62 $M_{\rm JUP}$ for the planet. The resulting mean density of 0.27 $\rm g\,cm^{-3}$ implies that the companion is a gas giant. It is tempting and certainly reasonable to suppose that all of the extrasolar planets found to date are gaseous, composed primarily of hydrogen and helium.

3. Three Planets Orbiting Upsilon Andromedae

The star Upsilon Andromedae is a normal main sequence star with mass of 1.3 $M_\odot$ and age of about 2 Gyr. The velocity measurements for this star show three periodicities, each consistent with Keplerian orbital motion of planets around the star. The only viable interpretation is that Upsilon Andromedae harbors three planets, making it the first solar system ever found, other than our own. The masses and orbits of the planets are listed in Table 1. The three Jupiter-mass planets are mutually stable against mutual perturbations, as shown by various N-body simulations (Laughlin & Adams 1999, Lissauer 1999).

Figure 3 shows the velocities for Upsilon Andromedae, after subtraction of the rapid velocity variations caused by the inner companion (Orbital Period = 4.6 d). The remaining velocities reveal two periodicities, well fit by the gravitational perturbations of the star caused by two outer planets. Interestingly, the two elliptical orbits of these outer two companions appear to be aligned, as their values for the orbital parameter, ω, are ω_c=239.6 and ω_c=241.2 deg. The possibility thus arises that these two outer planets reside in a mutual gravitational resonance that enhances their survival against mutual perturbations.

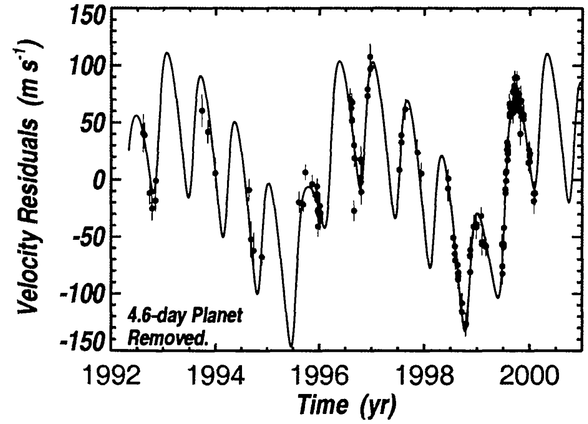

Figure 3. The measured velocities (points) of Upsilon Andromedae after subtracting the wobble caused by the innermost planet. The solid line shows the expected wobble from the outer two planets from simple Newtonian theory which evidently fits the measurements.

4. Disks Around Stars

4.1. Young Stars and Protoplanetary Disks

Most solar-type stars younger than ~3 Myr exhibit excess emission at infrared, UV, and radio wavelengths that is due to dust orbiting the stars. These protoplanetary, circumstellar dust disks contain gas and dust that is accreting onto the star (Hillenbrand *et al.* 1998; Lada 1999; Calvet *et al.* 2000). The thermodynamic properties of the disks, including masses, temperatures, accretion rates, and gas content are extracted from from measurements in UV through mm-wave observations (cf., Beckwith *et al.* 2000; Najita *et al.* 2000). The disks have masses from 0.01–0.1 $M_\odot$, large enough to build Jupiter-mass planets. The models of disks suggest that the dust will agglomerate into planetesimals and Earth-mass cores. An Earth-mass core would gravitationally attract gas, increasing its mass to that of Saturn and Jupiter (cf., Ruden 1999).

Models of the spectral energy distributions (SED) of young disks yield information about the dust temperatures and densities from thermal emission and light scattering properties. Remarkably, SEDs and images of disks reveal inner holes and truncated edges to disks. In a tour de force, Koerner *et al.* (1998) predicted the complete ring geometry around the 10 Myr–old star, TW Hya, from mid-IR images, with dramatic confirmation from HST NICMOS images (Schneider *et al.* 1999). The ring is naturally explained by gravitational perturbations by planets, similar to the shepherding of Saturn's rings (Goldreich & Tremaine 1980).

Protoplanetary disks no doubt consist of many ringlets, and have warps and azimuthal nonuniformities reminiscent both of Saturn's rings and of spiral galaxies. The disks are observed to flare outwards giving them a width that increases with increasing radius. Unfortunately, we know little about the temperature variation with height above the midplane, nor much about the turbulence, viscosity, and magnetic fields within the disks. However from the inner edge at 0.1 AU to the outer edges at 100 AU, the temperature varies between 2000 K to 10 K, providing a variety of molecules and condensates to survive in equilibrium locally. Future models should provide the structure needed to derive accurate disk properties and extract information about planetary perturbers (cf., Chiang & Goldreich 1999).

Planet formation may occur in the massive disks surrounding stars younger than the T Tauri stars. Most of a star's mass passes through its disk during the first 10^5 yr, implying disk masses of $\sim 0.1\,\mathrm{M}_\odot$, albeit short–lived. In such massive disks, dust growth may be more rapid and gravitational collapse of material may be important. The formation of Uranus, Neptune, the Kuiper belt comets, as well as close and eccentric Jupiter–mass objects may require massive disks (Boss 1998; Kenyon & Luu 1999; Armitage & Hansen 2000; Lunine *et al.* 2000).

Adaptive optics in the IR will permit 5 AU resolution of disks around the nearest T Tauri stars. Revealed inner holes and radial structure should yield thermal and dynamical models of disks and their planetary perturbers. Spatially resolved SEDs at mid–IR and sub–mm wavelengths will yield disk temperatures and densities as a function of radius. Near–IR spectroscopy at high resolution will provide a chemical assay of the gas and kinematic information (from line profiles) on sub–AU scales (Najita *et al.* 2000). Ground–based interferometry, SIRTF, and the Next Generation Space Telescope may cap a spectacular decade of protoplanetary disk work.

4.2. Middle–Aged Stars and Debris Disks

The Zodiacal dust and Kuiper Belt in the Solar System contain provides clues about the formation, chemistry, and dynamics during the past 4.5 Gyr (cf., Hahn & Malhotra 1999; Chiang & Brown 1999; Jewitt & Luu 2000; Holman *et al.* 2000; Ishiguro *et al.* 1999). The advent of high spatial resolution imaging at infrared and sub–mm wavelengths will provide similar information about planetary systems in general. Such images of disks reveal the inclination, i, of the ("ecliptic") orbital plane, thus giving us the mass of the planet directly from the Doppler measurements (without the troublesome $\sin i$). Observations of holes and gaps in the disks will may constrain the masses and orbits of shepherding planets (Kenyon *et al.* 2000; Schneider *et al.* 1999). The star 55 Cancri may foreshadow such disk value, as it seems to have two planetary companions, and its disk is observed in both scattered light (Trilling *et al.* 2000) and thermal emission (Jayawardhana *et al.* 2000).

Most intriguing is that the scattered light from middle-aged disks shows very little change in the color from that of the star itself from which the light originated (Koerner *et al.* 1998; Schneider *et al.* 1999). This wavelength–independent scattering suggests that the dust has agglomerated into large particles, over $10\,\mu$m in size. This evidence for dust growth provides an observational linchpin in the theory of planet formation.

The totality of evidence to date, from the common occurrence of protoplanetary disks to the 5% occurrence of Jupiter–mass planets, suggests that smaller planets are even more common. A reasonable extrapolation, with planet-formation theory as a guide, is that the majority of stars in the Galaxy harbor comet-sized and earth-sized orbiting companions.

Acknowledgments. Amy Reines, David Nidever, and Sabine Frink made valuable observations included in this paper. Eric Williams, Phil Shirts, and Chris McCarthy contributed analysis software. B. Walp made contributions to the manuscript. We acknowledge support by NASA (NAG5-8861) and NSF (AST95-20443) and by Sun Microsystems. We thank NASA and the University of California for their operation of the Keck and Lick facilities.

References

Armitage, P. J., & Hansen, B. M. S. 2000, *Nature*, in press

Artymowicz, P. 1993, *ApJ*, **419**, 166

Beckwith, S. V. W. , Henning, T., & Nakagawa,Y. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss & S. S. Russell, Univ. of Arizona Press, Tucson, in press

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., 1998, in *Brown Dwarfs and Extrasolar Planets*, ASP Conf. Ser. **134**, ed. R. Rebolo, E. Martin, & M. R. Zapatero Osorio, ASP, San Francisco, p. 354

Butler, R. P., & Marcy, G. W. 1997, in *Astronomical and Biochemical Origins and the Search for Life in the Universe*, Proc. of the 5th International Conference on Bioastronomy, held in Capri, Italy, IAU Colloq. No. 161, ed., C. Cosmovici, S. Bowyer, D. Werthimer., p. 331, Editrice Compositori, Italy

Calvet, N., Hartmann, L., & Strom, S. E. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Charbonneau, D. Brown, T. M., Latham, D. W., & Mayor, M. 2000, *ApJ Lett.*, **529**, 45

Chiang, E. I., & Brown, M. E. 1999, *AJ*, **118**, 1411

Chiang, E. I., Goldreich, P. 1999, *ApJ*, **519**, 279

Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. W. 1997, *ApJ*, **483**, 457

Goldreich, P. & Tremaine, S. 1980, *ApJ*, **241**, 425

Gonzalez, G., Wallerstein, G., & Saar, S. H. 1999, *ApJ*, **511**, L111

Guillot, R., Burrow, A., Hubbard, W. B., Lunine, J. I., Saumon, D. 1996, *ApJ*, **459** L35

Hahn, J., & Malhotra, R. 1999, *AJ*, **117**, 3041

Halbwachs, J. L., Arenou, F., Mayor, M., Udry, S., & Queloz, D. 2000, *Astron. Astrophys.*, **355**, 581

Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, *ApJ Lett.*, **529**, 41

Hillenbrand, L., Strom, S., Calvet, N., Merrill, K. M., Gately, I., Russell, B., Meyer, M., & Skrutski, M. 1998, *AJ*, **116**, 1816

Holman, M., Duncan, M., Levison, H., & Malhotra, R. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Holman, M., Touma, J., & Tremaine, S. 1997, *Nature*, **386**, 264

Ishiguro, M., Nakamura, R., Fujii, Y., Morishige, K., Yano, H., Yasuda, H., Yokogawa, S., & Mukai, T. 1999, *ApJ*, **511**, 432

Jayawardhana, R., *et al.* 2000, *ApJ*, submitted

Jewitt, D., & Luu, J. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss & S. S. Russell, Tucson, Univ. of Arizona Press) in press

Kenyon, S., & Luu, J. 1999, *ApJ*, **526**, 465

Kenyon, S. J., Wood, K., Whitney, B. A., & Wolff, M. J. 1999, *ApJL*, **524**, L119

Kirkpatrick, J. D. *et al.* 1999, *ApJ*, **519**, 802

Koerner, D. W., Ressler, M. E., Werner, M. W., & Backman, D. E. 1998, *ApJ Lett.*, **503**, 83

Korzennik, S., Brown, T. M., Fischer, D. A., Nisenson, P., & Noyes, R. W. 2000, *ApJ Lett.*, submitted

Lada, E. 1999, in *The Origin of Stars and Planetary Systems*, ed., C. Lada, & N. Kylafis, NATO Science Series, Kluwer, p. 441

Laughlin, G., & Adams, F. C. 1998, *ApJ Lett.*, **508**, 171

Laughlin, G, & Adams, F. C. 1999, *ApJ Lett.*, **526**, 881

Levison, H. A., Lissauer, J. J., & Duncan, M. J. 1998. *AJ*, **116**, 1998

Lin, D. N. C., & Ida, S. 1997, *ApJ*, **477**, 781

Lin, D. N. C. , Papaloizou, J. C. B., Terquem, C., Bryden, G., & Ida, S. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss, & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Lissauer, J. J. 1999, *Nature*, **398**, 659

Lunine, J. I., Owen, T. C., & Brown, R. H. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss, & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Marcy, G. W., & Butler, R. P. 1999, in *The Origin of Stars and Planetary Systems*, ed., C. Lada, & N. Kylafis, NATO Science Series, Kluwer, p. 681

Marcy, G. W., Cochran, W.D, & Mayor, M. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss. & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Mayor, M. Queloz, D. Udry, S., & Halbwachs, J.-L. 1997, in *Astronomical and Biochemical Origins and the Search for Life in the Universe*, Proc. of the 5th International Conference on Bioastronomy, held in Capri, Italy, IAU Colloq. No. 161, ed., C. Cosmovici, S. Bowyer, D. Werthimer, p. 313, Editrice Compositori, Italy

Najita, J, R., Edwards, S., Basri, G., & Carr, J. 2000, in *Protostars and Planets IV*, ed., V. Mannings, A. P. Boss & S. S. Russell, Univ. of Arizona Press, Tucson, in press

Noyes, R. W., Jha, S., Korzennik, S. G., Krockenberger, M., Nisenson, P., Brown, T. M., Kennelly, E. J., Horner, S. D. 1997, *ApJ Lett.*, **483**, L111

Prieto, C. A., & Lambert, D. L. 1999, *Astron. Astrophys.*, **352**, 555

Rasio, F., & Ford, E. B. 1996, *Science*, **274**, 954

Ruden, S. P. 1999, in *The Origin of Stars and Planetary Systems*, ed., C. Lada, & N. Kylafis, NATO Science Series, Kluwer, p. 643

Saumon, D., Hubbard, W. B., Burrows, A., Guillot, T., Lunine, J. I., & Chabrier, G. 1996, *ApJ*, **460**, 993

Schneider, G., Smith, B. A., Becklin, E. E., Koerner, D. W., Meier, R., Hines, D. C., Lowrance, P. J., Terrile, R. F., Thompson, R. E., & Rieke, M. 1999, *ApJ*, **513**, L127

Trilling, D. E., Brown, R. H., & Rivkin, A. S. 2000, *ApJ Lett.*, in press

Vogt, S. S., Marcy, G. W., Butler, R. P., Apps, K. 2000, *ApJ*, in press

Weidenschilling, S. J., & Marzari, F. 1996, *Nature*, **384**, 619

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