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Millennium Essay

Planets Orbiting Other Suns[1,2]

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ABSTRACT. After a century fraught with false claims, evidence for planets around other stars finally appears robust. Infrared imaging and spectroscopy of disks around stars foreshadow detailed models of the formation and evolution of planetary systems. Surveys of main-sequence stars show that 5% harbor companions of $(0.5–8)M_{\rm JUP}$ within 3 AU, peaked at lowest masses. Their orbits are either within 0.2 AU or eccentric, and occasionally both. These odd orbits suggest that dynamics with gas and planetesimals yield diverse systems and that stable, coplanar orbits of about nine giant and rocky planets may require special initial conditions. Far fewer stars ($<1\%$) harbor $(5–80)M_{\rm JUP}$ companions. This brown dwarf desert for companions stands in contrast to the abundant brown dwarfs that are freely floating.

1. INTRODUCTION

By the end of the century, evidence for extrasolar planets finally seemed secure. "The history of science offers no greater marvel than the discoveries of invisible planets moving round many of the stars which are now being made, and in which the Lick Observatory has recently taken the lead," wrote the great dynamicist Simon Newcombe in 1902 (Newcombe 1902). His stretched interpretation of W. W. Campbell's spectroscopic binaries nonetheless conveys two truths: (1) Over 100 years ago astronomers understood that Doppler-shift measurements could reveal planets around stars. (2) Astronomers (not only those at Lick) sustain a cultural tradition of fashionable foolishness. The mortuary of make-believe planets contains numerous tombstones, and many astronomers lugged these planets to their private graves, as chronicled by Dick (1996).

At the risk of perpetuating the morbid tradition, astronomers now point to three classes of observations which support the basic paradigm about the formation, existence, and evolution of planets. First, observations of disks around young stars agree with the disk properties required for the formation of our solar system, i.e., a flat, $\sim 0.03\ M_\odot$ disk, consisting of orbiting gas and dust (e.g., Beckwith, Henning, & Nakagawa 2000). Second, Doppler measurements of stars reveal unmistakable Keplerian motion implying the presence of Jupiter-mass companions, presumably the tip of the planetary mass distribution (e.g., Marcy, Cochran, & Mayor 2000). A third connection to the solar system stems from the IR and submillimeter (sub-mm) images of middle-aged stars that are surrounded by "debris disks," the presumed analogs of the Kuiper Belt and zodiacal dust (cf. Lagrange, Backman, & Artymowicz 2000; Jayawardhana et al. 2000). This essay describes our current speculations about extrasolar planets and future connections to our solar system.

2. DISKS AROUND YOUNG STARS

Solar-type stars younger than ~ 3 Myr exhibit signatures of circumstellar disks consisting of gas and dust accreting onto the star (Hillenbrand et al. 1998; Lada 1999; Calvet, Hartmann, & Strom 2000). Their masses, temperatures, accretion rates, dust and molecular content are derived from measurements spanning X-rays through millimeter-wave observations (cf. Beckwith et al. 2000; Najita et al. 2000). Their masses range from 0.01 to 0.1 $M_\odot$, large enough to construct a set of planets similar to those in the solar system. The resulting disk models suggest that the dust will agglomerate into planetesimals and Earth-mass cores. Such cores may gravitationally attract gas within a tidal (Hill) radius, leading to gas giant planets (cf. Ruden 1999).

Models of the spectral energy distributions (SEDs) 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, HR 4796, from mid-IR images, with dramatic confirmation from *Hubble Space Telescope*

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[1] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology, and based on observations obtained at Lick Observatory, which is operated by the University of California.

[2] The Essay is one of a series of invited contributions which will appear in the *PASP* throughout the year 2000 to mark the upcoming millennium. (Eds.)

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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).

Actual protoplanetary disks probably consist of multitudinous ringlets and have warps and azimuthal nonuniformities, reminiscent of Saturn's rings and spiral galaxies. Disks are not smooth nor flat nor uniform temperature. Structure should be included in models to derive accurate disk properties and to extract information on the planetary perturbers (cf. Chiang & Goldreich 1999).

One caveat is that we may be studying the wrong disks. T Tauri disks garner attention owing to their optical/IR visibility. But the bulk of a star's mass flushes through its disk during the first 10^5 yr, implying disk masses of ~ 0.1 $M_{\odot}$, albeit short-lived. In such massive disks, condensables grow quickly and gravitational instabilities may be important. The formation of Uranus, Neptune, the Kuiper Belt comets, as well as close and eccentric jupiters may require massive disks (Boss 1998; Kenyon & Luu 1999; Armitage & Hansen 2000; Lunine, Owen, & Brown 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.

3. PROPERTIES OF EXTRASOLAR PLANETS

Doppler surveys of ~ 500 main-sequence stars have revealed 28 "planets" of Jupiter-mass (cf. Marcy et al. 2000). The term "planet" inevitably conjures up specific images of circular and coplanar orbits, rocky and gaseous objects, and formation in a disk starting with condensables. The true properties of sub-$10M_{\rm JUP}$ objects around stars remain to be ascertained, and theory must provide the linkage from the observed properties to the physics of protoplanetary disks (Lin et al. 2000). Indeed, theory is challenged to explain the formation of the three Jupiter-mass companions orbiting Upsilon Andromedae, but their architecture already suggests that formation occurred in a disk (Butler et al. 1999).

To date, Doppler searches are sensitive to planets (and brown dwarfs) within 3 AU which have masses greater than $\sim 0.5M_{\rm JUP}$. Figure 1 shows the histogram of companion mass estimates drawn from all Doppler surveys of FGKM dwarfs, including six new planets (cf. Butler & Marcy 1997; Mayor et al. 1997; Halbwachs et al. 1999; Marcy et al. 2000; Vogt et al. 2000). The remarkable distribution of $M \sin i$ reveals a clear paucity from $8M_{\rm JUP}$ to $20M_{\rm JUP}$, but a rise from $8M_{\rm JUP}$ toward the lowest detectable masses, $0.5M_{\rm JUP}$, at which detection becomes poor. Several tentative conclusions might be drawn. Within 3 AU, there is a paucity of "brown dwarf" companions, relative to planets: fewer than 0.5% of surveyed stars have one. Free floating brown dwarfs, however, are abundant (Kirkpatrick et al. 1999). Planets rarely form with masses above $\sim 7M_{\rm JUP}$. The planetary mass distribution rises toward lower masses, not inconsistent with a power law, $dN/dM \propto M^{-1}$.

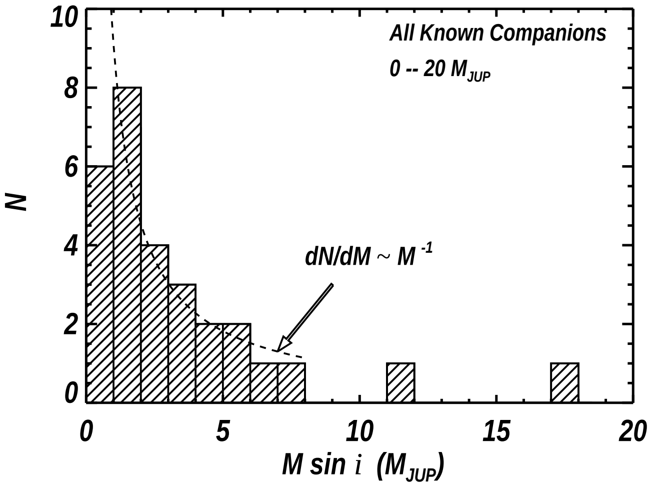

FIG. 1.—Measured values of $M \sin i$ for all known planet candidates around FGKM main-sequence stars. The rising mass distribution from $8M_{\rm JUP}$ to $1M_{\rm JUP}$ is real, and incompleteness is greatest below $1M_{\rm JUP}$. The planet mass distribution is consistent with $dN/dM \propto M^{-1}$. Brown dwarf companions, $M \sin i > 8M_{\rm JUP}$, are apparently rare within 5 AU.

Two other properties of the planets remain quite unexplained. The host stars of the extrasolar planets have higher abundances of the heavy elements by a factor of ~ 2 compared with field stars (Gonzalez, Wallerstein, & Saar 1999). Is this result a statistical fluke? If not, perhaps planets form more readily within dust-rich protoplanetary disks.

The orbits of the close-in 51 Peg planets are nearly circular, perhaps enforced by tidal circularization (cf. Lin et al. 2000). But all 18 planets that orbit farther than 0.2 AU from their star reside in noncircular orbits having $e > 0.1$, more eccentric than Earth ($e = 0.03$) or the giant planets ($e < 0.05$) (see Fig. 2). The large eccentricities may be explained by gravitational perturbations imposed by planetesimals, the disk, or passing stars (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Lin & Ida 1997; Levison, Lissauer, & Duncan 1998; Artymowicz 1993; Holman, Touma, & Tremaine 1997; Laughlin & Adams 1998). These theoretical models seem so robust as to convey an underlying principle. Entropy tends to disrupt circular, coplanar orbits. If so, our solar system is a special case, immune to severe instabilities. This bizarre possibility will

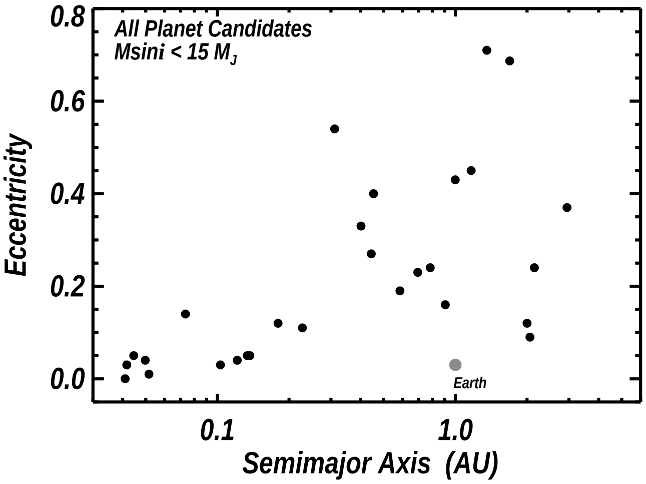

FIG. 2.—Orbital eccentricity vs. semimajor axis for all known planet candidates. Beyond 0.2 AU, all have noncircular orbits.

be tested by observations of jupiters at 4–6 AU, for direct comparison to our Jupiter.

4. ZODIACAL AND DEBRIS DISKS

The Kuiper Belt and the zodiacal dust in the solar system contain precious information 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). Infrared and sub-mm imaging of dust disks around other stars will yield comparable information about those planetary systems. Disk images give the inclination, i, of the orbital planes, and hence an unambiguous planet mass from $M \sin i$. The disk observations will reveal holes, gaps, and truncated edges, to provide dynamical information about shepherding planets (Kenyon et al. 1999, Schneider et al. 1999). The star 55 Cancri portends the future, as it may have two planets and a dust disk observed in both scattered light (Trilling, Brown, & Rivkin 2000) and thermal emission (Jayawardhana et al. 2000). Models of disk SEDs, their morphology, and the associated planets will produce a renaissance in planetary physics not seen since the *Voyager* missions.

The ubiquity of colorless, scattered light from dust around young and old stars suggests that agglomeration into large particles is common. There can be little doubt that the majority of stars in the Galaxy harbor comets and Earth-mass planets. The next 10 years will yield dozens of systems of planets, descriptions of their origin, and a measure of their diverse architectures. We may also glean ancillary features about planetary systems, such as their suitability for self-replicating organic molecules.

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