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An Outsiders View of Extrasolar Planets

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Abstract. We summarize the current state of extrasolar planet research, including the newest discoveries, properties of planetary systems, the current census, the mass function, and some thoughts on the formation and evolution of planetary disks.

1. Introduction

Let me begin by pointing out that Neill Reid wrote most of this talk, though he unfortunately couldn't be here to give it, so I am speaking in his stead. We chose the title "Outsiders View" to contrast with our previous "Insiders View" of brown dwarfs. We've recently completed a book on low mass stars and brown dwarfs (Reid & Hawley 2000), and thus feel justified in our insiders knowledge of that field. We make no such claim about extrasolar planets; indeed neither of us works in the field, and only by virtue of the organization of the meeting am I here giving this talk. Thus, I offer the caveat from the beginning that everything I say will be from published papers (mostly review papers) and that none of it will be my own work!

Having made that clear, I will proceed with this review of extrasolar planet research, outlining the initial discoveries, the current census, some of the major characteristics and some clues to their formation and evolution. I will also spend a few moments discussing nomenclature.

2. Discovery

The reflex orbital motion induced by planetary companions modulates stellar velocities; for example, Jupiter's influence on the Sun results in ~ 12 m s^{-1} amplitude variations in the solar radial velocity. High-precision radial velocity surveys have been undertaken since the mid-1980s (Walker et al. 1995; Marcy & Butler 1992; Latham et al. 1989; Duquennoy & Mayor 1991), but received relatively little attention from the wider community, until Mayor & Queloz' (1995) detection of near-sinusoidal low-amplitude velocity variations in the nearby solar-type star, 51 Peg. This discovery of the first unequivocal planetary companion, announced at CS9, was soon confirmed by Marcy & Butler (1995). The observed parameters are: $K_r = \pm 60$ ms^{-1}, P = 4.23 days, implying $M \sin i = 0.47\ M_J$, $a \sin i = 0.05$ AU — a Jovian-mass planet at sub-Mercurian

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siderocentric distance! **This is a complete mismatch to the Solar System Paradigm!**

There have been numerous subsequent discoveries by several groups, ably summarised at Jean Schneider's Extrasolar Planets Encyclopedia website (http://cfa-www.harvard.edu/planets/), including:

1. Fourteen more 'Hot Jupiters' (like 51 Peg B), with semi-major axis < 0.1 AU, $M \sin i > 0.1 M_J$.

2. sub-Saturnian mass systems, e.g. HD 168746b with $M = 0.24 M_J = 0.8 M_S$; P = 6.409 days (see Figure 1)

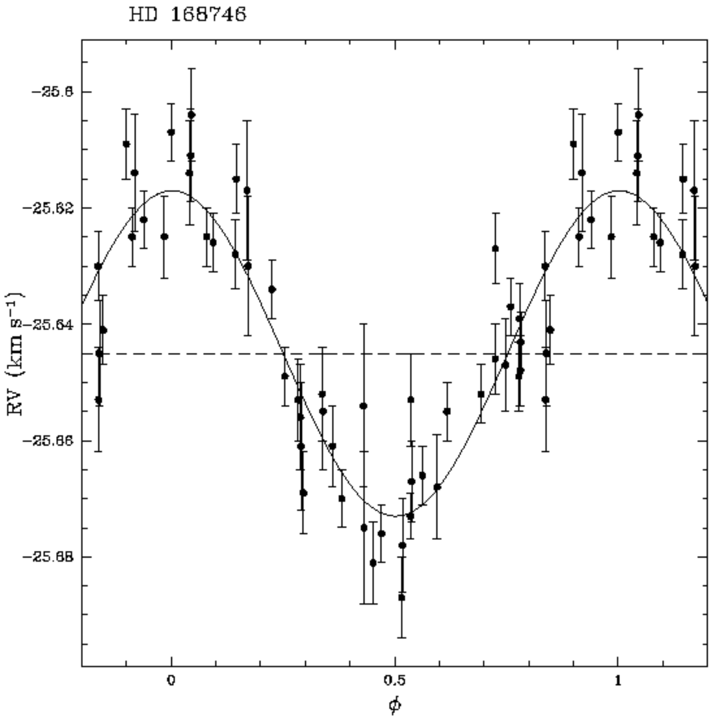

Figure 1. The velocity curve for the very low-mass system HD 168746b from the Geneva group's observations (see http://obswww.unige.ch/ udry/planet/).

3. Brown dwarf + planet systems, e.g. HD 168443, with components:
   b: $M \sin i = 7.2 M_J$, $a \sin i = 0.29$ AU, P = 57.9 days, e=0.54
   c: $M \sin i = 17.1 M_J$, $a \sin i = 2.87$ AU, P =5.85 years, e=0.2
   (see Figure 2)

4. Planetary systems, e.g. υ And, with components:
   b: $M \sin i = 0.71 M_J$, $a \sin i = 0.059$ AU, P = 4.62 days , e=0.034
   c: $M \sin i = 2.11 M_J$, $a \sin i = 0.83$ AU, P = 241.2 days, e=0.18
   d: $M \sin i = 4.61 M_J$, $a \sin i = 2.50$ AU, P = 1266.6 days, e=0.41

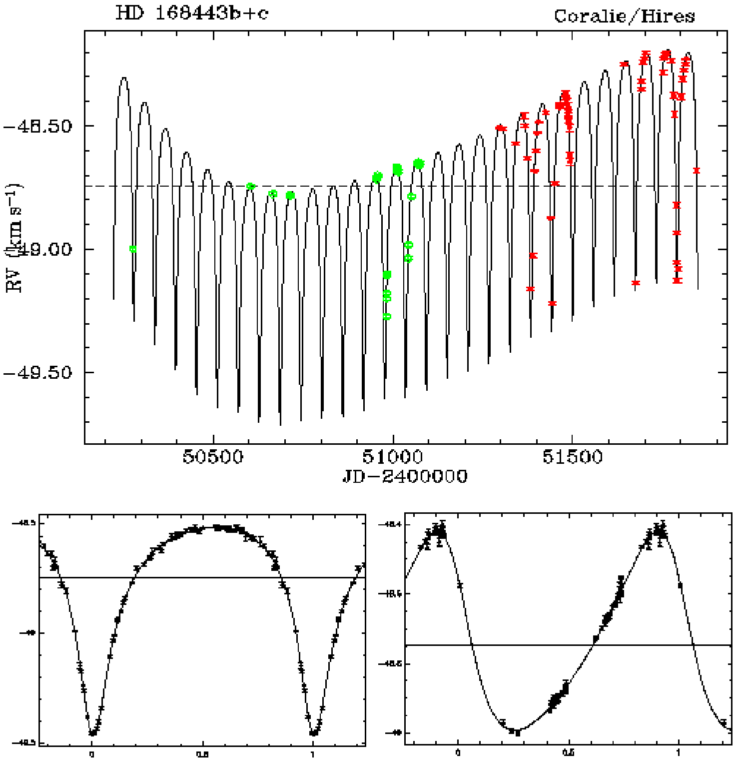

Figure 2. Velocity variations in the triple system, HD 168443, also by the Geneva group (http://obswww.unige.ch/ udry/planet/).

5. Planetary companions to low-mass stars, e.g. Gl 876 (sp type M4), with components:
   b: $M \sin i = 1.98 M_J$, $a \sin i = 0.21$ AU, P = 61.02 days , e=0.27
   c: $M \sin i = 0.56 M_J$, $a \sin i = 0.13$ AU, P = 30.1 days, e=0.12

6. Planetary companions in wide stellar binary systems, e.g. 16 CygB
   Bb: $M \sin i = 1.5 M_J$, $a \sin i = 1.70$ AU, P = 804 days , e=0.67
   HD 80606
   b: $M \sin i = 3.90 M_J$, $a \sin i = 0.439$ AU, P = 111.8 days , e=0.93

More extensive reviews of these developments are contained in Marcy & Butler (1998), Perryman (2000), Burrows, Hubbard & Lunine (2001) and IAU Symposium 202, Planetary Systems in the Universe.

3. A Planetary Census

All current confirmed discoveries are derived from radial velocity data. Surveys tend to concentrate on solar-type stars (late-F to early K), avoiding

1. Higher-mass stars – shorter lifetimes, younger, faster rotation, higher chromospheric activity

2. Low-mass K and M dwarfs – intrinsically low luminosity, low S/N spectra

3. Chromospherically active stars – 'jitter' in line profiles

all of which tend to produce lower-accuracy velocity data. In addition, close binary systems ($a < 10$ AU) are usually not included in surveys, as the binary may interfere in the formation of proto-planetary disks around the individual stars.

The measured parameters are P, e, $a \sin i$, $M \sin i$; current catalogues (see http://cfa-www.harvard.edu/planets/) include 65 planetary mass ($M < 10 M_J$) companions in 58 systems as of this writing. The primary stars range from F7 to M4 (~ 1.5 to $0.25 M_\odot$), and include several evolved stars (mainly subgiants). Figure 3 shows the Hipparcos HR diagram for nearby field stars; stars with planetary companions are indicated. Note the tendency of the planetary primaries to lie towards the upper edge of the main-sequence. This has been interpreted as a metallicity effect, such that metal-rich stars are more likely to have planets (Gonzalez 1997; see also Santos, this conference for more extensive discussion and references).

4. Frequency of Low-Mass Companions

Observational surveys to date have been subject to clear selection effects, including the program star selection (though current samples now comprise more than 1000 stars, and almost all solar-type stars within 25 parsecs of the Sun); inclination bias (we observe projected parameters, but the post-Copernican view expects random inclinations amongst a sufficiently large sample); and technical limitations (current velocity accuracy is ~ 5 m s^{-1}, and time baselines are $< 5 - 15$ years, favoring detection of higher-mass, shorter-period systems and making detection of Jupiter-analogues still at the threshold of possibility). Current statistics thus give a *lower estimate* to the frequency of planetary systems. With due deference to selection effects, the current statistics suggest:

- Solar-type stars: $\sim 5\%$ have detected companions

  $\sim 1.5\%$ have hot Jupiter companions

  $> 0.8\%$ have more than one planetary-mass companion

- M dwarfs: very few stars surveyed, but already one detection

  Do most Galactic planets orbit M dwarfs?

In comparison, stellar companion statistics (Udry et al. 2000) give:

- Solar-type stars: $\sim 9 \pm 2\%$ are SB, P < 1000 days; overall binary fraction, $\sim 70\%$

- M dwarfs: $\sim 11 \pm 3\%$ are SB, P < 1000 days; overall binary fraction, $\sim 35\%$

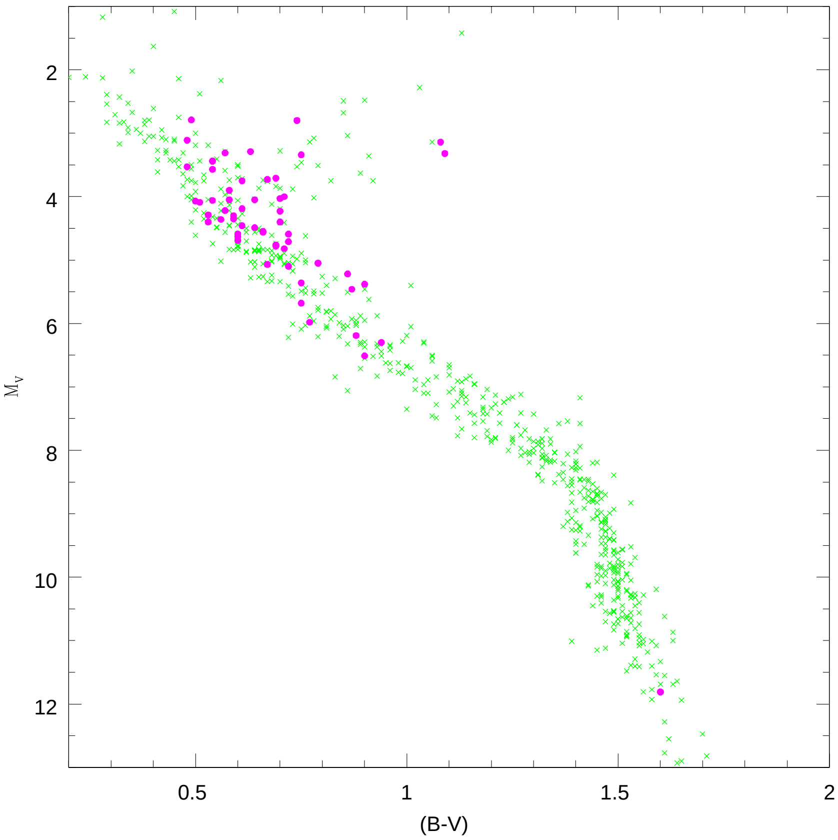

Figure 3. Hipparcos data for nearby stars. Systems with planetary-mass companions are identified as solid points.

The discrepancy in the overall binary fraction between solar-type stars and M dwarfs must reflect the relative number of wide binary systems. Indeed there is an observed trend between maximum separation and total system mass (Reid et al. 2001).

5. Orbital Characteristics

Pre-51 Peg, expectations were that planets would have circular orbits (as in the Solar System). In fact, circularity is common only for hot Jupiters, as shown in Figure 4. Most planetary orbits have significant eccentricity, with the highest value being that for HD 80606, e = 0.927. How are these elliptical orbits produced? Most likely through some kind of gravitational interaction, but this remains an open question. Possibilities include:

1. gravitational interactions with the protoplanetary disk – probably ineffective for very low-mass (planetary) companions due to damping effects

2. gravitational interactions with other planets – requires that there be other planets in the system
3. gravitational interactions with stellar companions – possible for HD 80606 (companion is HD 80607)

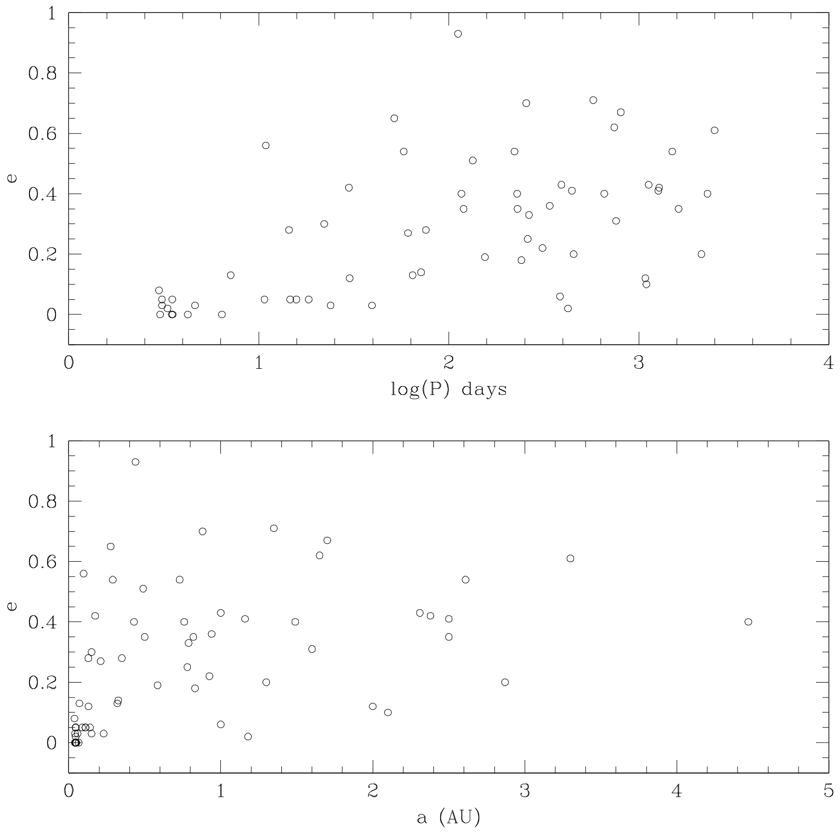

Figure 4. Orbital characteristics for the 65 planetary-mass companions

6. Planets or Brown Dwarfs?

Udry & Mayor (2001) show that a) G, K and M dwarfs share the same (e, log P) distribution for stellar binaries; and b) planetary-mass companions follow a very similar (e, log P) distribution. This is generally interpreted as indicating similar dynamical evolution for the two populations. However, Stepinski & Black (2001) take the similarity a step further, and suggest that both are drawn from the same *parent* population. Thus, they propose that 'extrasolar planets' are simply very low-mass brown dwarfs. Further, Han, Black & Gatewood (2001) analyse Hipparcos data for ESP primaries and claim to detect significant astrometric orbital motion. Taken at face value, those measurements imply $\sin i \ll 1$, $M_2 \gg M_2 \sin i$; in other words the companion masses are greatly underestimated, and all are either brown dwarfs or low-mass stars.

There are several problems with those arguments (see, for example, http://exoplanets.org/science.html). First, raising the mass estimates to brown dwarf levels requires inclinations $i \leq 2.5^o$, which occurs with probability $<$ 1/1000 for random i. Thus one would expect 999 detected BDs for each ESP, which is clearly not observed. Selection against known spectroscopic binaries does not vitiate this argument. Second, the derived orbital motions are compatible in scale with Hipparcos single-point uncertainties, and thus are liable to systematic bias in the analysis. The Hipparcos data has been analysed by Pourbaix (2001), Halbwachs et al. (2000), and Zucker & Mazeh (2001); all conclude that few, if any, of the proposed 'orbits' are significant.

7. The Mass Distribution

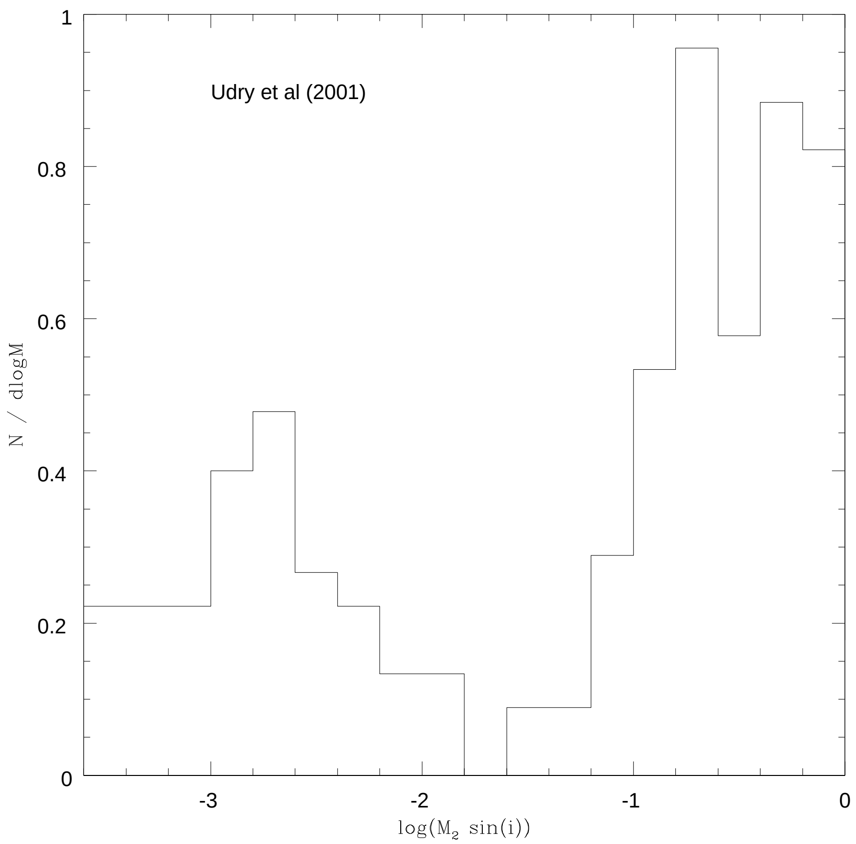

Figure 5. The mass distribution of low-mass companions to solar-type stars, from Udry et al. (2001).

Figure 5 shows the mass function for companions to solar-type stars, obtained by combining ESP data with G-dwarf spectroscopic binary (P $<$ 1000 days) data. Note the pronounced minimum from 0.08 to 0.02 $M_\odot$ which has been termed the "brown-dwarf desert". Binaries that appear in this range, with $0.02 < M_2 \sin i \leq 0.08$, tend to be low-inclination (i small) systems with stellar companions (Halbwachs et al. 2000; Zucker & Mazeh, 2001). Brown dwarf companions **are** found at large separation (Gizis et al. 2001). A tentative conclusion then, is that brown dwarf-mass objects seldom form in the protoplanetary disk regime, and that this figure is rather strong evidence for two separate populations of objects: ESP companions which form in disks, with a high mass cutoff near 0.02 $M_\odot$, and brown dwarf/stellar companions which form as binary star systems, with a low mass cutoff near 0.08 $M_\odot$. Indeed there was no *a priori* reason for the distributions not to overlap – perhaps this is a rare case where nature has been kind enough to avoid confusion!

The figure also shows no obvious feature at the Deuterium-burning mass limit ($\sim 0.013 M_\odot \sim 13 M_J$). The ESP distribution peaks at $\sim 2 M_J$, but the sample becomes increasingly incomplete at low masses, so this may well be an artifact. Marcy & Butler (2000) have shown that a distribution $dN/dM \propto M^{-1}$ is consistent with the ESP data, similar to $dN/dM \propto M^{-1.1}$ for low-mass stars and brown dwarfs (see the Brown Dwarf review paper by Hawley in these proceedings). This is a preliminary result, but the similarity is intriguing. Is this a common property of fragmentation processes?

8. What About 'Free-floating Planets'?

Sub-stellar mass objects fade rapidly with age, so very low-mass objects are most easily detected in young clusters ($\tau < 10$ Myrs). Several research groups have identified candidate very low-mass objects in young clusters such as σ Orionis and IC 348. Some of these groups refer to those objects as 'free-floating planets', 'isolated giant planets', 'planetary objects' and 'superjupiters'. Are these apellations appropriate? We compile here an admittedly personal and biased list of pros and cons.

Pro:

1. People (and funding agencies) like planets;
2. Purported very low-mass objects in clusters may have been expelled from planetary systems (i.e. they used to orbit a star);
3. Some perceive a need to discriminate between objects above and below the deuterium-burning limit, as is done with stars and brown dwarfs at the hydrogen burning limit.

Con:

1. The word *planet* already has a meaning in the vernacular. Re-defining terms which have well established meaning leads to unnecessary confusion; at the very least, a planet needs to be in orbit about some other body!

2. Simulations suggest that planet/planet interactions, and hence ejected planetary mass objects, are unlikely to account for more than a very small fraction of the total number (Bonnell et al. 2001);

3. a: Deuterium burning appears to have little or no significance in the evolution of extra-solar planets (Udry et al. 2001);
b: Unlike hydrogen fusion, the presence or absence of deuterium burning has little effect on long-term evolution, and, for all practical purposes, no observable consequences;
c: Mass estimates rest on theoretical models, with unknown reliability at $\tau < 10^7$ years, $T_{eff} < 3000$K. There are not yet any empirical mass measurements of low-mass pre-main sequence objects.

It is probably clear which side of the fence we're on. Why not just call these objects low-mass brown dwarfs? Or, if you must discriminate, how about "Giant Gas Balls In Space"! Accurate, and with no irrelevant (however profitable) associations.

9. Planet Formation: Protoplanetary Disk Evolution

Protoplanetary disks were identified originally based on excess mid-IR flux as shown in Figure 6. The disks are observed in scattered light at wavelengths $\lambda < 3\mu$m, and in re-radiated thermal emission at longer wavelengths. Disk evolution appears to proceed from embedded protostars and classical T Tauri stars with gas-rich disks, through transitional systems with dust-rich but gas-depleted disks, to debris disk systems with thin dust disks containing virtually no gas. Table 1 assimilates the properties of these evolutionary phases (see also Artymowicz 2000 for an extensive review of protoplanetary disk properties).

Disk Evolution Properties

Embedded protostar	L1551-IRS5	Gas-rich disk, $M \sim 0.1 M_\odot$
	$< 10^6$ years	$R \sim 100$ AU
Classical T Tauri	GG Tau, RY Aur, TW Hya	Optically-thick, gas-rich disk
	few $\times 10^6$ years	Strong CO emission
Transitional systems	HR 4796	Dust-rich, gas-depleted disk
	1-3 $\times 10^7$ years	little CO, some H_2
Debris disk	β Pic, Vega	Optically-thin dust disk
	$\sim 10^8$ years	essentially gas-free

TW Hydrae is a classical T Tauri star at a distance of $\sim$57 parsecs, with an age $\tau < 10$ Myrs, spectral type K7, and mass $\sim 1 M_\odot$. Its disk is viewed pole-on, and has a radius $\sim$4 arcsec $\equiv$ 225 AU. It has been detected by scattered light in the optical (WFPC2, Krist et al. 2000) and near-infrared (Figure 7; see also Schneider et al. 2001), in thermal emission in the mid-infrared (IRAS). It is also a strong CO source at millimeter wavelengths, indicating the presence of a gas-rich, optically-thick disk. The disk mass has been estimated as $\sim 0.03 M_\odot$ (Trilling et al. 2001).

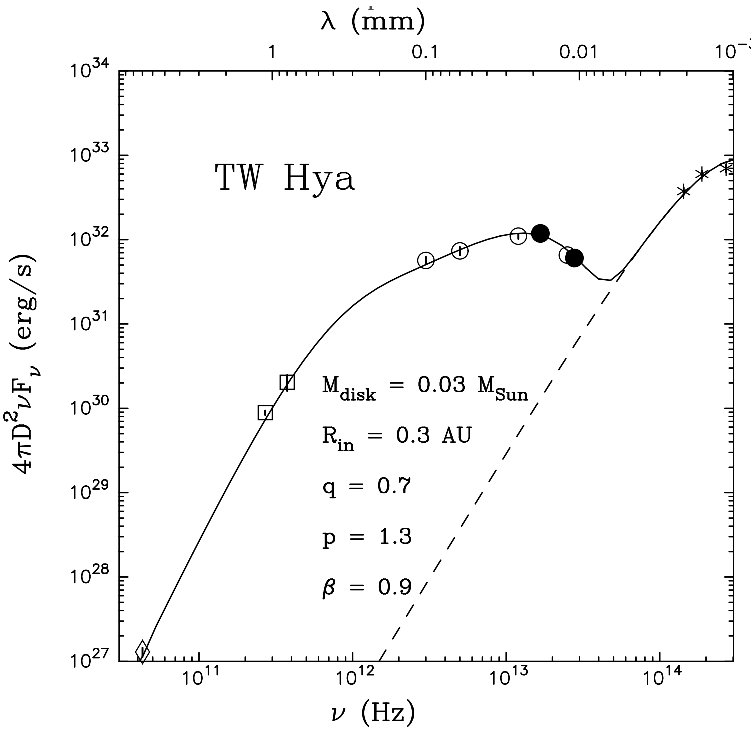

Figure 6. The energy distribution of the T Tauri star, TW Hydrae (from Trilling et al. 2001). The dashed line shows the long-wavelength extension of the photospheric energy distribution.

HR 4796 is a transitional disk system with distance ∼67 parsecs, age $\tau \sim 15-20$ Myrs, spectral type A0, and mass $\sim 2.5M_\odot$. It shows a strong IRAS excess at mid-infrared wavelengths, while the spectral energy distribution indicates a scarcity of warm dust, perhaps because of a central hole (Jura, 1991). It has a low gas content, with no CO detected in SEST/JCMT observations. Mid-IR images (Figure 8, also see Jayawardhana et al. 1998) show a disk viewed nearly edge-on with radius ∼ 200 AU. There is clear evidence for a central hole with R < 55 AU, confirmed by the structure seen in the NICMOS images. The disk dust mass is $\sim 0.25M_\oplus$ while the H_2 gas mass is $< 7M_\oplus$ ($< 2.1 \times 10^{-5} M_\odot$). Thus, the disk is essentially gas-free, and giant planet formation (if it occurred) must be complete in this system. Planetary-mass objects would provide an effective means of excavating the observed central hole, though no planets have yet been observed around HR 4796.

The archetype debris disk system is also the first one observed, β Pic. It is located at a distance of ∼16 parsecs, has age $\tau \sim 100$ Myrs, spectral type A5, and mass $\sim 1.7M_\odot$. A mild thermal excess was observed at mid-infrared wavelengths by IRAS, and the disk was first identified by Smith & Terrile (1984). The disk is viewed nearly edge-on, with a radius ∼ 250 AU, and has been detected in scattered light at optical and near-infrared wavelengths both from the ground and with HST. β Pic has a gas-poor, optically-thin disk, with $\frac{M_{gas}}{M_{dust}} < 0.1$; $M_{dust} \sim 0.44M_\oplus = 1.3 \times 10^{-6} M_\odot$ (Artymowicz, 2000). Thus $M_{gas} < 5M_{Moon}$!

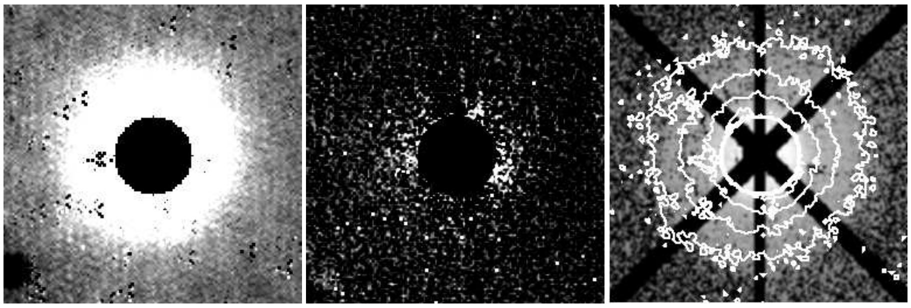

Figure 7. CoCo imaging of TW Hydrae (left); CoCo imaging of a reference star (center); Comparison of CoCo & HST WFPC2 data (right). Figure is from Trilling et al. (2001).

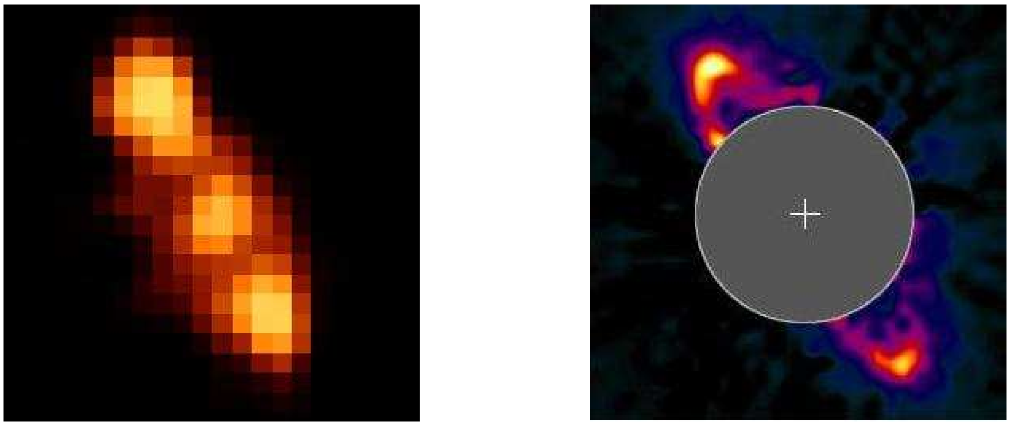

Figure 8. left: Keck/MIRLIN mid-IR image of HR 4796 (Koerner et al. 1998); right: HST/NICMOS near-IR image (Schneider et al. 1999)

The warps seen in images of the disk may reflect dynamical interactions with planets.

Taken together, these objects form an evolutionary sequence of disk properties that will be instrumental in understanding planetary formation. In particular, we can already see that the (young!) ages of the gas-depleted disks will place strong constraints on models for giant gas planet formation.

10. Current Issues and Future Prospects

Several important issues have emerged from our foray into the extrasolar planet literature:

1. How do extrasolar planets achieve eccentric orbits ?
   - presumably gravitational interactions, but with what??

2. How do giant planets form in <10 Myrs?
   - timescales are set by the observed evolution of disk properties
   - a problem for the old paradigm (Wetherill, 1994), a problem for the new
3. How do hot Jupiters form?
   - orbital migration within the protoplanetary disk?
   - what stops the migration - disk depletion?
4. Is planet formation really limited to high metallicity stars?
   - is there a low metallicity cutoff?
   - might metal-poor stars form smaller planets?
5. How common are terrestial planets and solar system analogues?
   - is the Solar System special, or do we just need to look harder?

Technological innovations will soon provide enhanced capabilities for detecting and studying extrasolar systems, including:

- Improved timelines for radial velocity monitoring
- Improved astrometric capabilities (milliarcsecond precision): Ground-based interferometry - CHARA, Palomar (PTI), Keck, VLT
  Space-based interferometry - $< 50\mu$arcsec precision with SIM
  Longer term $\rightarrow$ TPF (NASA), Darwin (ESA)
- Improved spatial resolution:
  Ground-based adaptive optics + interferometry - Keck, VLT
- Improved data on disk evolution:
  SIRTF will provide mid-infrared imaging and spectroscopy
- New detection methods:
  Ground-based transit surveys - wide-field imaging of $> 10^5$ targets
  Space-based transit surveys - Kepler (NASA), Eddington (ESA)

11. Summary

Extrasolar planet research has emerged as a mature subject, with both concrete and tantalizing results in its short (6 year) history. Among these are:

1. At least 5 % of G dwarfs (perhaps of all stars?) have attendant planets;
2. It is highly probable that ESPs are not an extension of a BD population – similarities in orbital properties may reflect similar dynamical evolution, rather than similar formation scenarios;
3. The ESP mass function is tantalisingly similar to that for stars/brown dwarfs – a global characteristic of fragmentation?;
4. The current ESP sample remains strongly biased and incomplete; but
5. Technological advances offer the potential for further significant advances in the near future.

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