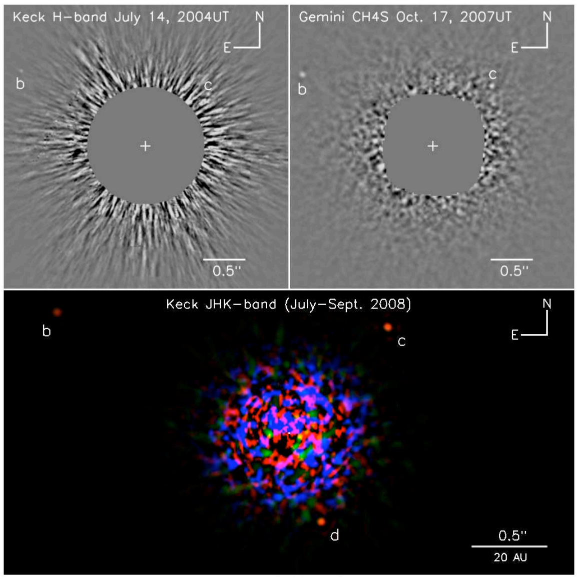
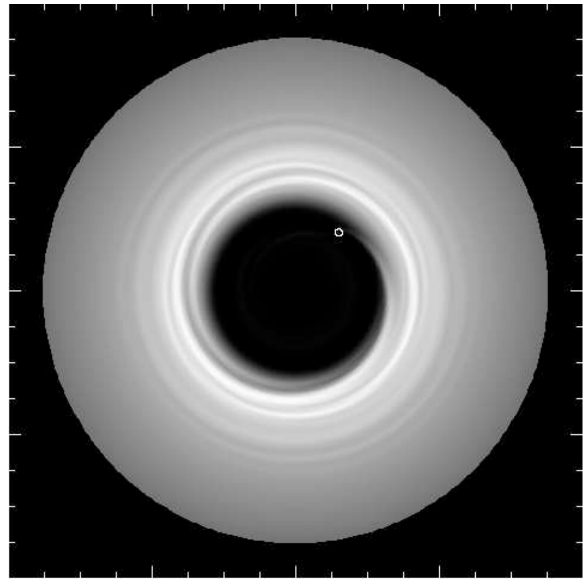
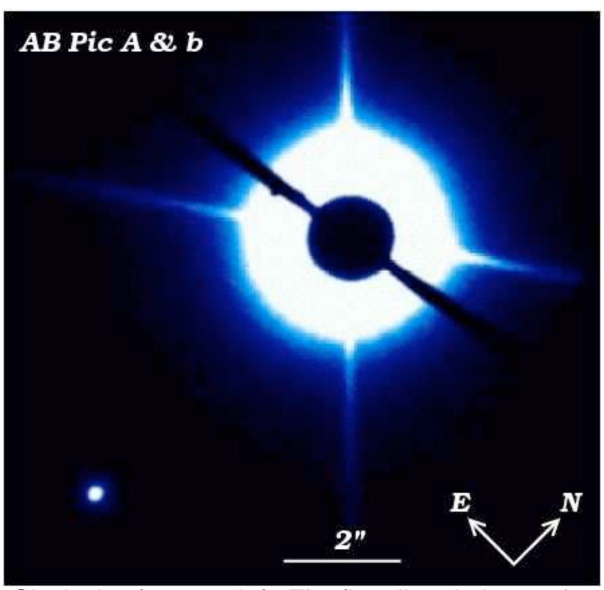


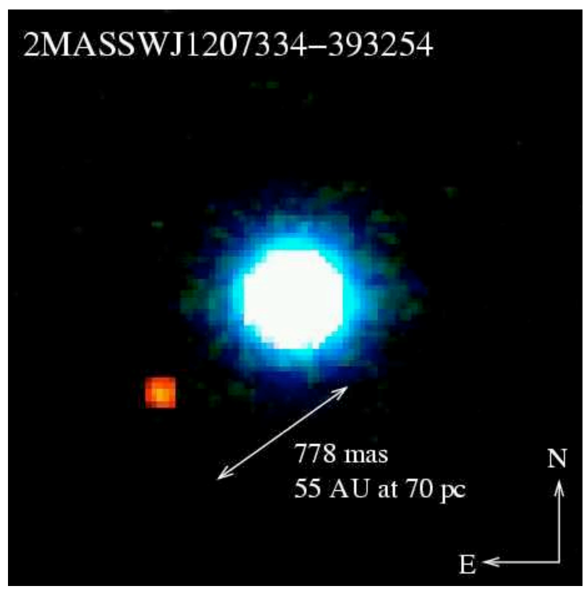


The Formation and Architecture of Young Planetary Systems

An Astro2010 Decadal Survey White Paper

Adam Kraus (Caltech), **Kevin Covey** (Harvard/CfA), **Michael Liu** (Hawaii/IfA), **Stanimir Metchev** (SUNY Stony Brook), **Russel White** (Georgia State), **Lisa Prato** (Lowell), **Doug Lin** (UCSC), **Mark Marley** (NASA Ames)





Clockwise from top left: The first directly-imaged extrasolar planetary system, HR 8799 bcd[1]; a model of how a giant planet would clear a protoplanetary disk[2]; the wide, apparently planetary-mass companions 2M1207b and AB Pic b[3,4].

Contact Information for Primary Author:
A.L. Kraus, California Institute of Technology
(626) 395-4095, alk@astro.caltech.edu

Abstract

Newly-formed planetary systems with ages of $\lesssim$10 Myr offer many unique insight into the formation, evolution, and fundamental properties of extrasolar planets. These planets have fallen beyond the limits of past surveys, but as we enter the next decade, we stand on the threshold of several crucial advances in instrumentation and observing techniques that will finally unveil this critical population. In this white paper, we consider several classes of planets (inner gas giants, outer gas giants, and ultrawide planetary-mass companions) and summarize the motiviation for their study, the observational tests that will distinguish between competing theoretical models, and the infrastructure investments and policy choices that will best enable future discovery. We propose that there are two fundamental questions that must be addressed: 1) Do planets form via core accretion, gravitational instability, or a combination of both methods? 2) What do the atmospheres and interiors of young planets look like, and does the mass-luminosity relation of young planets more closely resemble the "hot start" or "cold start" models? To address these questions, we recommend investment in high-resolution NIR spectrographs (existing and new), support for innovative new techniques and pathfinder surveys for directly-imaged young exoplanets, and continued investment in visible-light adaptive optics to allow full characterization of wide "planetary-mass" companions for calibrating planet evolutionary models. In summary, **testing newly proposed planet formation and evolutionary predictions will require the identification of a large population of young ($<$10 Myr) planets whose orbital, atmospheric, and structural properties can be studied.**

Introduction

The exciting discovery of extrasolar planets just over a dozen years ago has revitalized stellar and planetary science and generated a tremendous public interest in astronomy. Since then, an immense international effort has demonstrated that $\gtrsim$10-15% of FGK-type stars harbor extrasolar giant planets[5]. Surprisingly, however, the properties of many of these planets are radically different from the gas giant planets in our solar system. Some orbit their host star at a small fraction of an AU in less than a week's time, while others have highly eccentric, binary star-like orbits[6,7]. Planet-like companions (if evolutionary models are correct), have even been directly imaged at separations of more than 100 AU from their host star [3,4,8]. These unexpected properties forced sweeping changes in the standard picture of how disk material assembles into planets[9]. Unfortunately testing these new theories is extremely difficult because of the lack of direct observational constraints.

Currently, the two competing paradigms for forming extrasolar giant planets (EGPs) are the core accretion and gravitational instability models[10,11]. Core accretion provides a natural explanation for the enhanced EGP frequency around metal-rich stars[12,13] and the massive solid cores of many EGPs[14,15,16]. Also, core accretion should proceed most rapidly at the snow line, with subsequent migration of the resulting gas giants to smaller radii, so the model naturally explains the gas giant population at $<$5 AU discovered by field RV surveys. However, the core accretion timescale is unrealistically long at radii of $>$10 AU[17], so it can not explain wide exoplanets like Fomalhaut b[8] and HR 8799 bcd[1], much less the ultrawide planetary-mass companions like 2M1207 b[3]. The rapid collapse and growth of gravitational instabilities in a protostellar or protoplanetary disk provides a more feasible explanation for the formation of wide systems, so it appears that both processes contribute to the overall exoplanet population. Surveys for young exoplanets are critical for distinguishing the relative importance of each process.

The atmospheres and interior structure of young exoplanets are also completely unconstrained by current observations. The mass-luminosity-age relation is very sensitive to the formation scenario (the “hot start” versus “cold start” models)[18,19,20]. The predicted luminosities vary by as much as 2-3 orders of magnitude, so the first empirically measured fundamental properties of young exoplanets (i.e. temperatures and luminosities) will provide an unambiguous endorsement of one set of models. The predicted yield from future direct imaging surveys, and therefore the relative merits of imaging and astrometric missions, depends critically on the assumed mass-luminosity relation. The first handful of ground-based detections with existing technology will allow us to finally calibrate young EGP models, determining the missions that should be supported for 2020 and beyond.

Both of these open questions must be addressed at the age range when planets form, before evolution obscures the signatures of their formation mechanism (via migration and planet-planet interactions) and primordial interior structure (via radiation of the primordial energy from assembly). This age range is set by the disk dissipation timescale ($\lesssim$10 Myr)[21] and the timescale for the “hot-start” and “cold-start” models to converge ($\sim$10 Myr at 2 M_{Jup})[19], encompassing most of the star-forming regions in the solar neighborhood. One notable feature is the large distance to these populations; aside from a few sparse moving groups, all stars younger than $\sim$10 Myr are located at distances of $\gtrsim$120 pc, which strongly limits the choice of observing strategies.

Ground-breaking results from Spitzer have revolutionized our understanding of protoplanetary disk formation, and the rapid pace for discovery of nearby exoplanets has transformed our understanding of old planetary systems. However, the difficulty of identifying young planets has left us few clues on the early evolutionary processes that transform protoplanetary disks into architecturally mature systems; *as we begin the next decade, the field has yet to identify even one young exoplanet*. In this white paper, we describe the science drivers and observational goals that should guide young exoplanet science in the coming decade. The critical questions and observations fall into three regimes that will be probed via different techniques: the inner solar system (via radial velocity surveys), the outer solar system (via extreme AO imaging and interferometry), and ultrawide substellar companions (via deep coronagraphic imaging). Our policy recommendations (bold face at section ends) are aimed at ground-based surveys; recommendations for space surveys can be found in papers by Beichman (SIM) and Sivaramakrishnan (JWST).

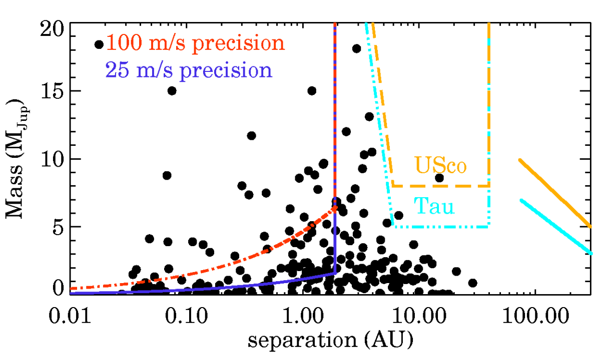


Figure 1. Projected limits for the survey methods we describe. For RV surveys, we show the limits corresponding to measurement precisions of 100 m/s (red) and 25 m/s (blue). For aperture masking, we show the limits in Taurus (1-2 Myr; dashed cyan) and Upper Sco (5 Myr; dashed orange) given the achieved contrast limit ($\Delta L = 6 - 7$ at Λ/D) and the models of Baraffe et al. (2002). For wide PMCs we show similar limits (solid lines) for obtaining a spectrum with S/N $\sim$10 and R $\sim$1000 in 6 hours on a 10m telescope with visible-light AO.

Table 1. *Open Problems and Solutions for the Next Decade*

Observable Test	*Theoretical Constraint*	*Observation*
How quickly do planets form?	Core Accretion or Grav. Instability?	RV, Imaging
Planets at wide separations or the snow line?	Core Accretion of Grav. Instability?	Imaging
How bright are the most massive planets?	"Hot Start" or "Cold Start" Models?	Imaging
When do Hot Jupiters appear?	Constraining Migration Timescales	RV
Do planets open most of the gaps in disks?	How ubiquitous are planets?	Imaging
What are the properties of wide "planets"?	"Hot Start" or "Cold Start" Models?	Visible-Light AO

Revealing Hot Jupiters Through High-Precision Infrared Spectroscopy

Determining the frequency of young hot Jupiters, as well as their physical and orbital properties, will provide new, empirical constraints for models of planet formation and migration. Even accounting for errors in age estimates for young stars[22], it will be hard to reconcile a dearth of planets around stars younger than 3 Myrs with the gravitational instability model, which predicts planet formation timescales much shorter than 1 Myr[11]. The distribution of orbital separations and eccentricities, and their evolution with age, will provide a strong test for models of planetary migration; similarly, if the formation of gas giant planets is indeed the dominant mechanism driving circumstellar disk dispersal, then we expect an elevated planet frequency for stars whose disks have large inner holes or gaps. Finally, one of the most compelling reasons to search for young hot Jupiters is that $\sim$1/10 will transit their host star. The size and density of a planet are strictly constrained by its transit depth and shape, and its atmosphere can be studied through transmission spectroscopy[23]. Even a handful of these systems would yield unprecedented constraints on the composition and structure of planets immediately after formation.

Building a significant sample of young hot Jupiters, as required to define the frequency and timescale of gas giant formation, will only be possible through precise radial velocity (RV) monitoring in the near–infrared. Most young stars are too distant (d$\geq$120 pc) to detect planets within $\sim$1 AU via direct imaging or astrometry, and photometric variability due to accretion and flares make transit detections virtually impossible. Most perniciously, starspots distort optical spectral lines as they rotate across the surface of young stars, mimicking RV signals due to planets[24]. The young, actively accreting classical T Tauri star TW Hydrae provides a cautionary tale: RV periodicity was detected in the optical and, after careful scrutiny, attributed to a planet[25]. Follow-up observations with CRIRES, a high resolution (R$\sim$100,000) near-infrared (NIR) spectrograph on the VLT, found that TW Hydrae's RV signature is strongly wavelength dependent and disappears entirely in the H band (Figure 1)[26]. These observations corroborate predictions that RV anomalies are minimized in the NIR due to lowered contrast between Rayleigh-Jeans emission from starspots and the surrounding photosphere; Prato et al. recently confirmed this effect[27].

While NIR Doppler observations indicate that TW Hydrae does not host a gas giant, the star's stability at 35 m/s precision demonstrates that this technique will detect young gas giants elsewhere. Accumulating even a moderately sized sample of young planets, however, will require a significant investment of observational resources; if young stars host planets with the same frequency as nearby solar analogs this will require monitoring hundreds of young stars. Although the global astronomical community currently lacks the capacity for a survey of this scale, pioneering efforts with available (but outdated) US facilities demonstrate the feasibility. RV surveys have obtained precisions of 100 m/s

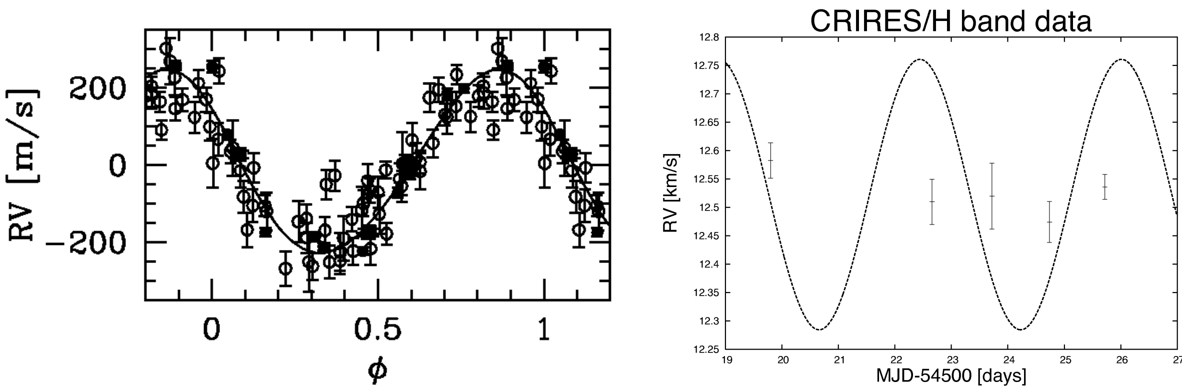


Figure 2. Left: Phase-folded RV measurements of TW Hya obtained with the optical spectrographs HARPS, CORALIE, and FEROS. The best Keplerian fit has a semi-amplitude of 238 m/s, and was initially interpreted as reflex motion due to a planet[25]. Right: Infrared RV measurements of TW Hya obtained with CRIRES show that its RV is constant to within 35 m/s and suggest the variations seen at optical wavelength are due to star spots.[26] (Figures from Huélamo et al. 2008).

with CSHELL at IRTF[27] and 50 m/s with NIRSPEC at Keck[28]; next generation instruments should yield even better results[29,30,31]. Nevertheless, the demonstrated stability of CRIRES on the VLT and the upcoming commissioning of NAHUAL on the Gran Telescopio de Canarias[32] present a challenge for continued US competitiveness. **Ensuring that U.S. investigators lead this area over the coming decade will require significant community access to existing high-dispersion NIR spectrographs and development of new instruments to expand the U.S. capacity for measuring precise RVs in the NIR.**

Unveiling Outer Planetary Systems with Innovative Direct-Imaging Techniques

The frequency and properties of outer extrasolar giant planets (EGPs) at a *∼5–40 AU will provide crucial constraints on the process and ubiquity of planet formation.* Direct imaging surveys present the only realistic prospect for studying these long-period planets since RV and astrometric surveys would require decades-long monitoring campaigns. These surveys are best conducted for very young systems since young EGPs are more luminous than their older brethren, significantly reducing the contrast between stars and planets, though the distance to nearby star-forming regions ($d \geq$120 pc) imposes a corresponding resolution penalty. Planetary systems undergo significant dynamical evolution after birth, so it is also important to study the most architecturally pristine systems.

Planet formation models now form Jupiter and Saturn in situ, via core accretion in ∼3 Myr, which is also the disk dissipation timescale[21,33]. These competing timescales make the outer EGP frequency a sensitive test of formation models, as significantly changing either would make outer EGPs scarce or ubiquitous. The planet formation timescale also distinguishes between formation models; a paucity of EGPs at $<$2-3 Myr would argue that planets form slowly via core accretion, whereas the existence of planets around the youngest stars would require a prompt process like gravitational instability. Finally, core accretion is fastest at the snow line[34], indicating that many EGPs should form at ∼3-5 AU and migrate inward. A broader orbital distribution would argue that some EGPs form via gravitational instability, though this test is only significant at young ages; interactions with planetesimals or other planets can scatter EGPs outward within ∼50-100 Myr[35]. The distribution of EGPs also will reveal the gaps within which terrestrial planets could form.

Ongoing planet/disk interactions will also provide new insight into the planet formation process. Many nearby young stars show firm observational evidence of gaps or inner holes with radii of 10-40 AU (see cover figures); these "transitional disk" systems are identified from SED modeling[36,37,38] or spatially resolved submm/mm imaging[39]. If these gaps are signposts of ongoing planet formation, then they show exactly where to search for the youngest, most luminous exoplanets. Furthermore, if most gaps host planets, it would indicate that a large fraction of disks are cleared by planet formation; empty gaps might indicate that photoevaporation clears most disks, forestalling EGP formation.

The current generation of planet-search instruments, including GPI and SPHERE, are optimized to deliver high contrast ($\sim$10^4-10^6) at wide separations ($>$0.5") to search for planets around nearby stars. Young planets are much brighter, but because their host stars are more distant, most planets will fall inside the instruments' coronagraph radius ($\sim$200 mas or $\sim$30 AU). In the long term, extreme AO systems on ELTs could identify Jupiter analogues (a $\sim$5 AU; M $\sim$1 M_{Jup}) around young stars. However, this decade will be dominated by existing telescopes that use new instruments or techniques to search for massive Jupiter analogs (a $\sim$5-10 AU; M $\sim$5-10 M_{Jup}).

One of these promising techniques is aperture-mask interferometry[40,41,42] (Figure 3), which achieves superior contrast limits over imaging at small separations ($\sim$10^2-10^3 at Λ/D) by resampling a single telescope aperture into a sparse interferometric array. This technique can achieve detection limits of $\sim$7-10 M_{Jup} at ages of 5 Myr and $\sim$5 M_{Jup} at 1 Myr. There are also ongoing plans for a masking survey with JWST that will achieve contrasts of 10^4–10^5 (see paper by Sivaramakrishnan). On a $\sim$3-5 year timeframe, extreme AO systems on existing telescopes will also be commissioned, including PALM3K at Palomar and NGAO on Keck. The superior AO performance with respect to current imaging techniques could surpass aperture-mask interferometry. The continued availability of telescope time for these surveys will also be critical; most current initiatives are using private facilities like Keck and Palomar, but to remain competitive with ongoing European programs at the VLT, we must open the field to the entire US community with either increased access to the private observatories or improved flexibility in bringing outside technologies to Gemini. **The mass-luminosity relation of young exoplanets and the population statistics of outer gas giants are undetermined, so pathfinder surveys that exploit new instruments and techniques at existing observatories will be critical in guiding next-generation missions from space and with the TMT/GMT.**

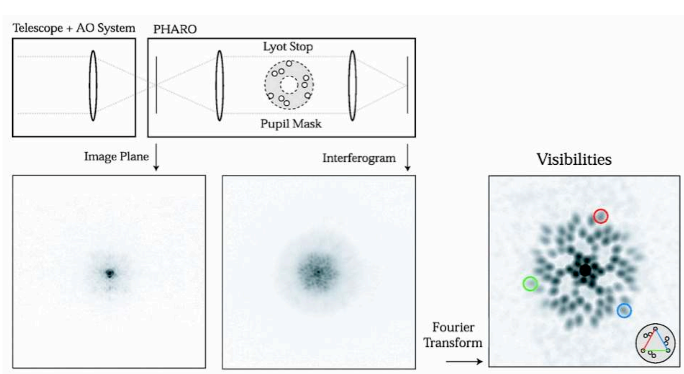


Figure 3. Schematic of aperture-mask interferometry, one experimental high-resolution imaging technique implemented at Keck and Palomar. A mask transforms the single aperture into an interferometric array, yielding an interferogram. A Fourier transform recovers the visibilities. This technique represents only one opportunity for discovering exoplanets; **openness to experimental instruments and techniques is one of the strongest advantages of our private observatories and should be extended to our national system.**

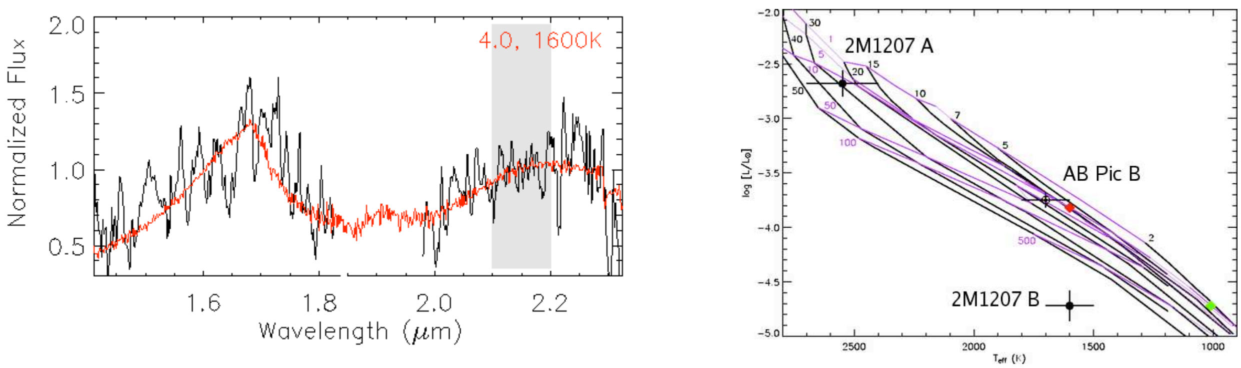


Figure 4. Left: NIR spectrum of 2M1207b (black), an apparently planetary-mass companion with an age of ~8 Myr and a spectral type of ~L6; models predict a corresponding mass of ~5-8 M_{Jup}. The red line shows a SETTL model spectrum with $\log g = 4.0$ and $T_{eff} = 1600$ K.[46] Right: The positions of 2M1207b and AB Pic b on an HR diagram, plus the isochronal (black) and isomass (purple) lines of the Lyon models (Baraffe et al 2002). The position of AB Pic b agrees very well with its age, but 2M1207b is significantly underluminous. **Placing a planetary-mass object on an HR diagram should be regarded as an outstanding success for our field, but significant uncertainties in their properties and provenance must be addressed in the coming decade.**[46] (Figures and results from Mohanty et al. 2007).

Calibrating Young Exoplanet Models with Wide Planetary-Mass Companions

Over the past five years, direct imaging surveys for extrasolar planets have discovered a small but significant number of planetary-mass companions (PMCs) at $>$50 AU separations from their primaries (see cover page). The prototypical system, 2M1207-3933, consists of a 4 M_{Jup} companion located ~50 AU away from a 10 Myr old brown dwarf[3]. Since its discovery, ~5 other PMCs have also been reported, most of which orbit much higher-mass primaries (~0.5–1.5 $M_\odot$). PMCs pose a significant challenge to existing models of planet formation. The core accretion timescale ($>>$100 Myr at 100 AU[17]) is far longer than the disk dissipation timescale ($\lesssim$3-5 Myr[21]). Gravitational instability could form PMCs[11], but only for disks that dwarf the most massive systems currently observed (~0.05 $M_\odot$[43]). Binary formation also is unable to explain PMCs, as theoretical simulations are unable to produce extremely unequal-mass companions[44] and PMCs are too common to represent the extreme tail of the observed binary mass function[42,45].

Wide PMCs are far easier to study than their analogs in normal planetary systems, so their atmospheres and interiors provide an empirical baseline for models of young gas giant planets. The luminosities of young exoplanets are currently uncertain by as much as ~2 orders of magnitude[18,19,20], so it is critical to determine whether these companions are genuinely 5-15 M_{Jup} (as is predicted by mass-luminosity relations). This issue is complicated by PMCs' uncertain origin; if they form via binary fragmentation or via gravitational instability in a massive protostellar disk, then they might not have the same interior structure and evolutionary history as conventional exoplanets.

Past studies of PMCs were limited to NIR photometry and spectroscopy (Figure 4) due to their extreme faintness and the current limits of AO. NIR techniques are sufficient for PMC discovery, but new results for young brown dwarfs show that NIR SEDs are severely impacted by condensate cloud levels, leaving NIR observations weakly diagnostic of PMCs' physical properties[47,48]. Optical fluxes and spectra are much less affected, yielding accurate measurements of temperature, metallicity, and surface gravity, but they are difficult to acquire. Current AO systems do not operate shortward of 1μm, and the small aperture of HST is insufficient for optical spectroscopy. It is also important to study indicators of their formation process such as accretion (from Hα emission) or disk evolution (from atypical SEDs due to reflected starlight, as for Fomalhaut b)[8].

Coupled with these empirical tests is the need for theoretical advances in atmospheric models themselves. Beyond the complex processes of condensate cloud formation and chemistry in dynamic atmospheres, models also require improvements in chemical abundances and opacities. Currently, there are large uncertainties in the absolute abundances of CNO in our reference standard, the Sun[49,50]. CNO-bearing molecules are a dominant source of opacity in planetary atmospheres, so abundance uncertainties translate into systematic uncertainties in atmosphere models. Models also suffer from incomplete warm opacity line lists for key molecules; line lists at wavelengths $<$1.6 μm are incomplete for CH_4 and nonexistent for NH_3. These molecules produce strong absorption bands that leads to substantial flux redistribution, propagating spectral modeling errors to other wavelengths. Calculating the very large number of transitions for these molecules is computationally intensive, while the supporting laboratory studies remain challenging.

Existing telescopes and instruments are sufficient for the continued discovery of very wide planetary-mass companions, but we lack the capabilities needed to characterize their fundamental properties and formation history. Visible-light AO systems on large-aperture telescopes, capable of both imaging and spectroscopy, will be crucial in extending our studies into the optical regime; initiatives like PALM3K at Palomar and NGAO at Keck will lead the field. Visible-light AO will also be required to study detailed accretion processes and reflected light from circumplanetary disks; further advances in visible-light AO will eventually even allow the direct study of reflected optical light from young planets at smaller radii. **Resolved planetary-mass companions will provide templates for the atmospheric properties of all young exoplanets, so we must support the observational advances in visible-light AO and computational advances in atmospheric physics that are needed to characterize their formation, atmospheres, and interiors.**

References
1. Marois, C. et al. 2009, Science, ref
2. Quillen, A. et al. 2004, ApJ, 612, 137
3. Chauvin, G. et al. 2004, A&A, 425, 29
4. Chauvin, G. et al. 2005, A&A, 438, 29
5. Butler, R.P. et al. 2006, ApJ, 646, 505
6. Fischer, D. et al. 2008, ApJ, 675, 790
7. Jones, H. et al. 2006, MNRAS, 369, 249
8. Kalas, P. et al. 2008, Science, 322, 1345
9. Santos, N. et al. 2005, Science, 310, 251
10. Ida, S. & Lin, D. 2004, ApJ, 616, 567
11. Boss, A. 2001, ApJ, 563, 367
12. Gonzalez, G. 1997, MNRAS, 285, 403
13. Fischer, D. & Valenti, J. 2005, ApJ, 622, 1102
14. Saumon, D. & Guillot, T. 2004, ApJ, 609, 1170
15. Sato, B. et al. 2005, ApJ, 633, 465
16. Guillot, T. et al. 2006, A&A, 453, 21
17. Pollack, J. et al. 1996, Icarus, 124, 62
18. Baraffe, I. et al. 2003, A&A, 402, 701
19. Marley, M. et al. 2007, ApJ, 655, 541
20. Fortney, J. et al. 2008, ApJ, 683, 1104
21. Haisch, K. et al. 2001, ApJ, 553, 153
22. Hillenbrand, L. & White, R. 2004, ApJ, 604, 741
23. Charbonneau, D. et al. 2002, ApJ, 568, 377
24. Huerta, M. et al. 2008, ApJ, 678, 472
25. Setiawan, J. et al. 2008, Nature, 451, 38
26. Huélamo, N. et al. 2008, A&A, 489, 9
27. Prato, L. et al. 2008, ApJ, 687, 103
28. Bailey, J. et al. 2009, in prep
29. Edelstein, J. et al. 2007, SPIE, 6693, 26
30. Jones, H. et al. 2008, SPIE, 7014, 31
31. Ramsey, L. et al. 2008, PASP, 120, 887
32. Martín, E. et al. 2005, AN, 326, 1026
33. Dodson-Robinson, S. et al. 2008, ApJ, 688, 99
34. Ida, S. & Lin, D. 2008, ApJ, 685, 584
35. Levison, H. et al. in ”Protostars & Planets V”, 669
36. Calvet, N. et al. 2005, ApJ, 630, 185
37. Espaillat, C. et al. 2007, ApJ, 670, 135
38. Brown, J. et al. 2007, ApJ, 664, 107
39. Brown, J. et al. 2008, ApJ, 675, 109
40. Tuthill, P. 2000, PASP, 112, 555
41. Lloyd, J. et al. 2006, ApJ, 650, 131
42. Kraus, A. et al. 2008, ApJ, 679, 762
43. Andrews, S. & Williams, J. 2005, ApJ, 631, 1134
44. Bate, M. 2009, MNRAS, 392, 590
45. Metchev, S. & Hillenbrand, L., ApJS, in press
46. Mohanty, S. et al. 2007, ApJ, 657, 1064
47. Cruz, K. et al. 2009, AJ, 137, 3345
48. Herczeg, G. et al. 2009, ApJ, in press
49. Asplund, M. et al. 2005, ASPC, 336, 25
50. Lodders, K. et al. 2009, A&A, in press