Direct Detection and Spectroscopic Characterization of Giant Extrasolar Planets

A white paper to the 2010 Decadal Survey

Bruce Macintosh (LLNL)
macintosh1@llnl.gov
925-423-8129

James Graham (UC Berkeley), Mark Marley (NASA Ames), Hannah Jang-Condell (U. Maryland)
Travis Barman (Lowell Observatory), Laird Close (University of Arizona), Philip Hinz (University of Arizona), Michael Liu (University of Hawaii), Ben Oppenheimer (American Museum of Natural History), Karl Stapelfeldt (JPL)

1. Introduction

The study of exoplanets is in its initial stage of exploration, a stage that will persist through 2010-2020. During the upcoming decade, direct detection—spatially separating the light of a planet from its parent star—will become increasingly important. Already, results (Kalas et al 2008, Marois et al 2008) show the power of this technique; with the advent of AO coronagraphs such as the Gemini Planet Imager (GPI) or SPHERE in 2011, hundreds of warm Jovian planets may be detected. By 2020 advanced high contrast imagers in space and GSMT will bring mature solar systems within our reach.

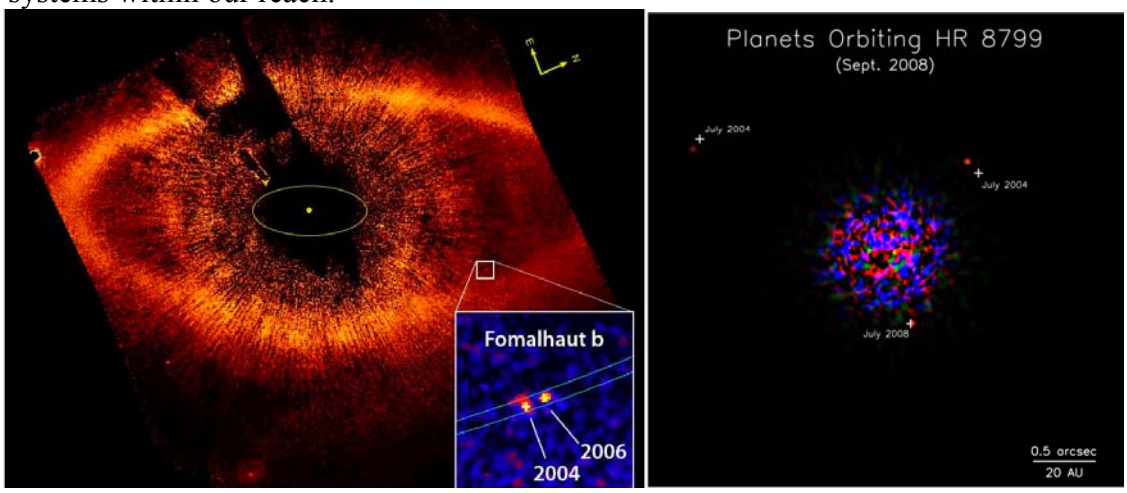

Figure 1: *Left*: Coronagraphic images showing the exoplanet Fomalhaut b (Kalas et al. 2008). Inset shows the orbital motion from 2004 to 2006. *Right*: Three massive planets orbiting HR8799 (Marois et al 2008). Earliest known positions are marked with +.

In the next decade, reflex motion, transits, and microlensing will be used to discover terrestrial planets, yielding orbital information, masses, and radii in the best cases. The exploration of the physics of planet formation, structure, and evolution will focus on giant planets ($M > 10M\oplus$ with hydrogen envelopes.) This white paper explores the science that direct detection and spectroscopic characterization of giant planets will enable in the study period. Key priorities for exoplanets in this epoch are

- Accumulation of exoplanet statistics to enable quantitative tests of the formation and evolution of solar systems.
- Exploration of solar systems beyond the frost line including mapping of Jovian mass planets outside of 5 AU.
- Complete sets of orbital elements to investigate the dynamical state of exoplanets.
- Detection and spectroscopy of light from exoplanet atmospheres to study their atmospheres, measure effective temperature, gravity, and composition.
- Reconstruction of the thermal history of Jovian planets to explore the early stages of formation.
- Inventorying Jovian mass planets hosted by early F and A stars to understand how mass and luminosity of the host star impacts planet formation.
- Explore and delineate the relationship between exoplanets and debris disks.
- Study the formation of planetary systems *in situ*

Realizing these will require significant investments in dedicated instruments and theoretical capabilities

- Support for large-scale surveys using the next generation of AO coronagraphs on 8-m telescopes
- Development of technology leading ultimately to deployment of an advanced AO coronagraph on GSMT and development and flight of a >1m space-based coronagraphic telescope
- Support for theoretical modeling of giant planet atmospheres
- Improved opacities for major giant-planet atmosphere constituents (e.g. methane)
- Robust determination of target-star ages from 3 Myr to several Gyr to study the whole process of planetary evolution

1.1. Capabilities of direct imaging

High contrast imaging systems can be characterized by a inner working angle (IWA), the smallest offset at which a planet can be detected, and a contrast at which a source can be reliably seen. For example, Jupiter is ~ 10^{-9} fainter than the sun; at 20 pc the separation would be 0.25". Typical IWAs will be 2-5 λ/D_{tel}. Near-future systems on 8-m telescopes should routinely achieve near-IR contrasts of 10^{-7} at 0.15". This allows detection of self-luminous giant planets through their retained heat of formation at ages of up to 1 Gyr for massive planets (Figure 3). Similar instruments on Extremely Large Telescopes may exceed contrast of 10^{-8} with IWA of 0.04". At this level, almost any self-luminous planet can be characterized at high SNR and spectral resolution, and mature planets in the inner parts of solar systems (<2 AU) become detectable through reflected light. Dedicated space coronagraphs may achieve visible-light contrast of 10^{-9} or even 10^{-10}, though their smaller aperture will limit IWA to 0.2" even at short wavelengths. These systems will most likely be integral field spectrographs rather than simple imagers, allowing R~50-100 spectroscopy of any detectable planet.

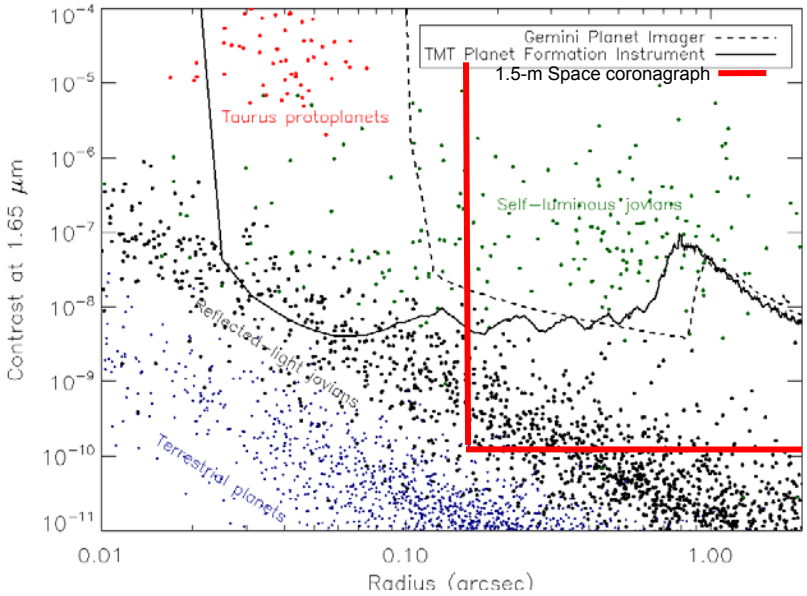

Figure 2: Contrast vs. separation for notional exoplanet populations, showing the terrestrial planets (lower left), Jovian planets (black: old jovian planets seen in reflected light; orange: younger self-luminous planets) and accreting protoplanets in Taurus (top left). Contrast curves are for 8-m and 30-m telescope ExAO systems (at 1.65 μm) and a high-performance 1.5-m space coronagraph (at 0.8 μm) are shown.

2. Exoplanet statistics beyond Doppler searches

Although there is preliminary information regarding the statistics of mass and semimajor axis of exoplanets, the current catalogs suffer from incompleteness for masses below 0.3 M_J and periods longer than 5.5 years; moreover, the samples are too small to explore multivariate properties of these distributions.

Approximately 5% of targeted stars reveal Doppler-detected planets. The abundance of circumstellar disks suggests that the frequency of planetary systems may be as high as 15 to 50%. The low detection rate of planets may be a consequence of the biases inherent to detection of orbital motion. So far, none of the Doppler surveys have the precision or lifetime necessary to detect Jupiter and thus do not yet constrain the frequency of solar system analogs. By 2020 Doppler searches will have reached 8 AU and Doppler plus direct searches that explore outer solar systems (4-40 AU) would increase the total number of planets found relative to those in inner solar system orbits (0.4-4 AU) given than the underlying distribution of planets in $\log(a)$ is at least flat if not rising (Cumming et al. 2008). For a surface density law that meets the requirements of the minimum solar nebula ($\Sigma \sim r^{-3/2}$) such a search would approximately quadruple the total number of known planets.

Doppler surveys reveal a diversity of exoplanet systems, but they leave long-standing and new questions unanswered: How do planets form? Is our solar system typical? What is the abundance of planetary systems? What produces the dynamical diversity in exoplanetary systems? Direct imaging can answer these questions by offering a fast alternative to Doppler surveys for searching the greatest stellocentric distances for planets. Characterizing the frequency and orbital geometries of planets beyond 3 AU will enable us to answer whether configurations like our own planetary system are commonplace. Direct detection will also reveal the zone where planets may form by direct gravitational instability and uncover traces of planetary migration, and open up spectral types (A and early F) and ages (<1 Gyr) that are poorly suited to Doppler techniques. Ironically, as the hosts of debris disks, that A stars were the first known population to host disks of planetesimals and planetary embryos; however, only with the advent of direct imaging do we know now that these stars, e.g., Fomalhaut and HR8799, host planets (Figure 1).

Searches in the outer parts of solar systems will sample the regions where Jovian planets are thought to form, and quantify the greatest distance out to which giant planets can occur. The outer limit for planet formation depends on at least two competing factors: time-scales for planet building and the availability of raw material. Dynamical and viscous time scales are shorter at small radii, while for typical surface density laws the amount of mass increases with radius, with a jump in the abundance of solid material at the "snow line". The discovery of giant planets far beyond the snow line would tend to favor theories of planet formation by gravitational instability over solid core condensation and accretion. Beyond about 30 AU gas-cooling times become shorter than the Keplerian shearing time—a necessary condition for runaway gravitational instability (Gammie 2001; Johnson & Gammie 2003; Boss 2002)—while core growth by coagulation of planetesimals proceeds prohibitively slowly (Goldreich, Lithwick, & Sari 2004).

A third reason to image the outer regions of extrasolar systems is to probe them for vestiges of planetary migration. Ninety percent of Doppler exoplanets lie within 3 AU, suggesting that they have migrated inwards. A variety of mechanisms may drive orbital evolution; the tidal gravitational interaction between the planet and a viscous disk (Goldreich & Tremaine 1980), the gravitational interaction between two or more Jupiter-mass planets (Rasio & Ford 1996), and the interaction between a planet and a planetesimal disk (Murray et al. 1998). If

planets form while the disk is being dispersed, or if multiple planets are present, outward migration can also occur. The observed Doppler exoplanet eccentricity distribution can be reproduced if the 51 Pegasi systems are formed by planet-planet scattering events and the second planet typically remains bound in a wide (a > 20 AU), eccentric orbit (Rasio & Ford 1996; Marzari & Weidenschilling 2002). Clearly, observations of the incidence, mass, and eccentricity distributions of multiple planet systems are needed to understand how planetary orbits are sculpted.

3. Planetary characterization

Direct detection of extrasolar giant planets offers the opportunity to characterize planets at large orbital separation and opens an important new window into understanding the process of planetary formation and evolution in other stellar systems. Characterization of giant exoplanets begins with constraining mass, radius, and bulk composition and moves on to measuring atmospheric composition and recognizing important global processes, like cloud condensation, stratospheric heating, atmospheric dynamics, and photochemistry. By studying not only planetary *architectures,* but also *processes*, direct imaging and spectroscopy brings studies of extrasolar planets into the realm of comparative planetary science, as has been practiced within the solar system over the past sixty years. Understanding the challenges inherent in characterizing giants will also serve to inform future efforts to interpret the spectra of extrasolar terrestrial planets.

The most fundamental measure of a planet, of course, is mass. This can be estimated for luminous young planets by comparison with evolutionary models, as has been done for the planets orbiting HR 8799. The properties of young planets depend upon the initial conditions established during their formation and thus such mass determinations are currently highly uncertain. However, as more planets are imaged around stars of varying ages as well as free-floating planet mass brown dwarfs in young clusters, our knowledge of planet formation will improve and the systematic errors will be reduced. Direct detection of planets also detected by radial velocity or astrometric methods or with masses determined from mutual interactions or other dynamical methods (e.g., the mass of Fomalhaut b is constrained by its interaction with the stellar dust disk) will ultimately serve to calibrate the evolution models.

Beyond mass, spectroscopy of the light from planets opens their atmospheres to the study of temperatures, gravities and compositions. These objects represent planetary *terra incognita*. For example, at T_{eff}'s below 400–500 K water condenses in planetary atmospheres; a second major transition is expected to occur below 180 K when NH_3 clouds form. The appearance of water ice clouds constitutes a significant milestone along the path from the known T dwarfs to the giant planets. Associated with condensation is the depletion of the gas-phase abundance of that species above the cloud tops. Within 100 Myr, water clouds form in the atmosphere of an isolated 1 M_J object. The presence of clouds of any sort emphasizes the kinship of this transitional class with solar system planets, in which clouds play a prominent role.

The atmospheres of all of the solar system giants are enhanced in heavy elements over solar composition, by factors ranging from 4 to 50 for various elements and planets. Generally the enhancement increases with distance from the sun and with falling mass. The detailed pattern of the enhancement is taken to be a signature of the planet formation process and the subsequent accretion of planetesimals into the atmospheres of the giants. The details of this interpretation in the solar system remain controversial. A measure of the atmospheric composition for many different planetary systems will thus provide important new tests for

planetary formation theory. We are already on the cusp of such discovery with the three planets orbiting HR 8799. Even relatively low-resolution, near-infrared spectra of these planets will reveal their gross composition. The substantial work that has already been done to understand the well-studied brown dwarfs paves the way for such studies and validates much of the spectral modeling approaches. The presence of absence of cloud layers, which can also be discerned from low-resolution spectra, also serves as a atmospheric composition and temperature indicator.

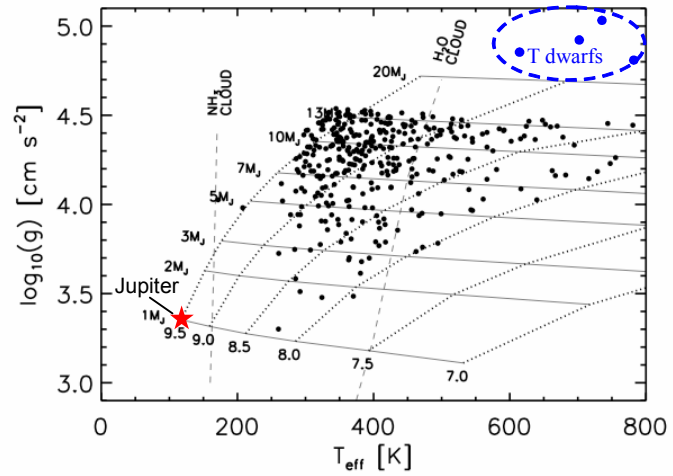

Figure 3: The surface gravity/T_{eff} diagram for exoplanets. Hot, young jupiters detectable with near-future AO systems lie at the center of this figure—solid dots can be detected by the Gemini Planet Imager. Solid curves are evolutionary tracks; dotted curves are isochrones (Burrows et al. 2003). Condensation curves for H_2O and NH_3 are dashed lines. The coolest known T dwarfs are in the upper right (Burgasser et al. 2006; Warren et al. 2007). Mature, solar-system planets (4.5 Gyr) are located at the lower left. Space coronagraphs or GSMT AO will be capable of detecting mature planets from 0.3 M_J or lower filling the 100-800K regime. The planets characterized by transit techniques occupy a narrow region off the far right of the graph.

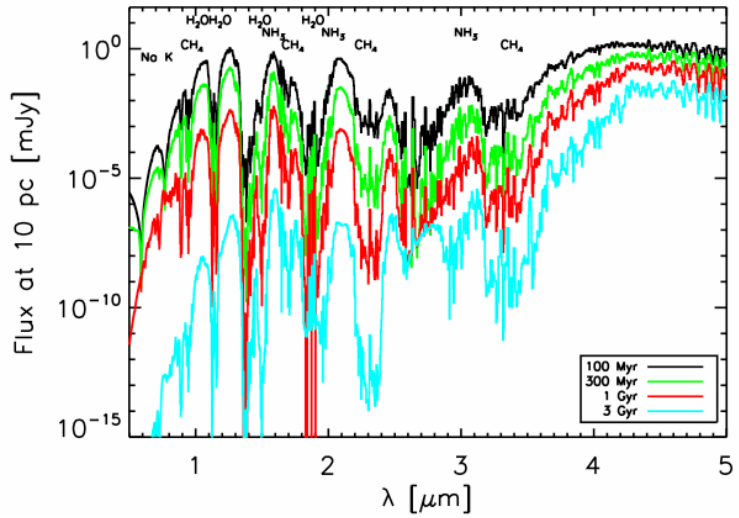

Figure 4: Spectra of a 5 M_J exoplanet as a function of age showing the distinctive peaks due to enhanced flux between the water vapor absorption bands (0.93, 1.1, 1.4, 1.8 & 6.5 μm) typical of brown dwarfs. Other general features are the broad hump at 4.5 μm, CH_4 features at 1.7, 2.2, & 3.3 μm and the NH_3 features at 1.5, 1.95, & 2.95 μm. The strengths of each of these features are functions of mass and age.

A wide gap in T_{eff} and log g exists between the currently known T dwarfs and cool, solar Jovian planets (see Figure 3). However, these objects must exist as the youthful progenitors of

the known population of Doppler-detected exoplanets. Figure 4 shows theoretical spectra of a 5 M_J exoplanet as a function of age showing the distinctive peaks due to enhanced flux between the water vapor absorption bands. Thus, the ground-based near-IR *YJHK* bands, which are defined by the same H_2O opacity, are ideal bands in which to seek detection.

4. Imaging the process of planet formation

With the advent of AO-equipped 25 to 40-m Extremely Large Telescopes, ground-based near-IR astronomy will be able to achieve angular resolutions of 10 mas or better—even for complex or high-contrast objects. This opens up the possibility of observing the planet formation process itself in nearby young associations or star-forming regions, where 1 AU subtends less than 10 mas. Bright, actively accreting planets may be directly detectable, particularly if they have opened gaps in their host protoplanetary disk. Even if the optical depth to the planet is high, rowing planet cores embedded in gas-rich protoplanetary disks can locally perturb the disk structure, resulting in shadows at the surface of the disk which may be observable at high angular resolution. The gravitational potential of the planet pinches the disk in the vertical direction, creating a shadow at the planet's position. The far side of the dimple is exposed to more direct stellar illumination, and is therefore brightened. In Figure 5 we show simulated scattered light images of planet cores of various masses and distances at 1 and 3 μm, respectively (Jang-Condell, in prep). The spatial scale and contrast of the shadow increase with planet size and approximately linearly with the distance between the planet and the star.

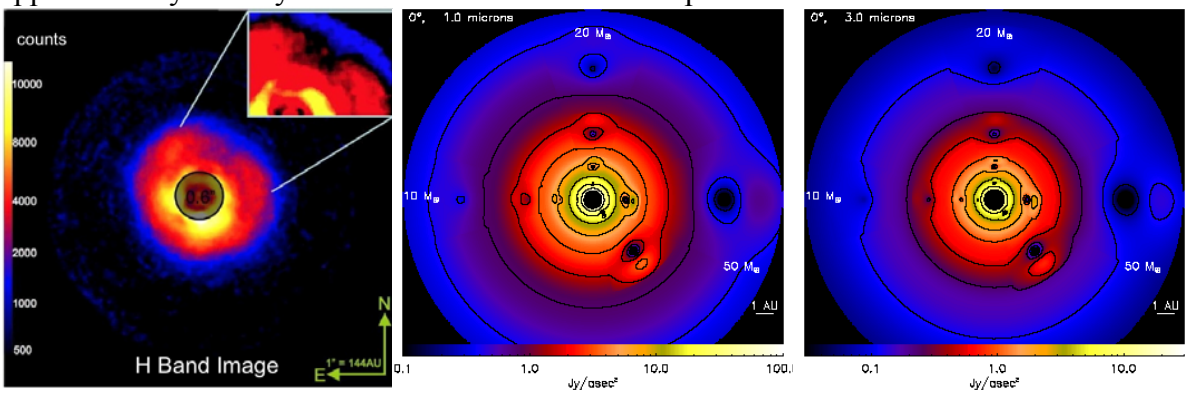

Figure 5: Recent scattered polarized light observations of the Herbig Ae star AB Aur show evidence of a shadow in the disk that could indicate the presence of a planet (Oppenheimer, et al. 2008). Scattered light images of planet cores of various masses and distances.

5. Thermal history and formation

The standard theory for the formation of gas giant planets is the core-accretion model (e.g., Pollack et al. 1996), which begins with dust particles form icy and rocky planetary cores. If the core becomes massive enough while gas remains in the disk, it continues to grow by gravitational accretion of this gas. Gas giants accrete most of the gas within their tidal reach filling the Hill sphere around them with a hot, extended, gaseous envelope. Further accretion is slowed by the dwindling supply of local raw materials and by the extended envelope, leading to growth times of 5–10 Myr.

Marley et al. (2007) and Fortney et al. (2008) have conducted preliminary calculations that describe the cooling and contraction of a young planet as it emerges from its disc (Figure 6). The implication of these results is that giant planets formed by the core accretion-gas capture mechanism are less luminous *post-accretion* than had been previously appreciated. There are two

significant observational consequences: 1) there is a period of very high luminosity (likely broader and fainter than in the idealized calculations above); 2) the initial conditions for evolution models are not "forgotten" for tens of millions of years. These factors imply that observations of planets near class II (0.5–3 Myr) and III (< 20 Myr) young stellar objects, particularly if their mass can be independently determined, afford the opportunity the probe the planet formation event in ways that distinguish between different formation scenarios.

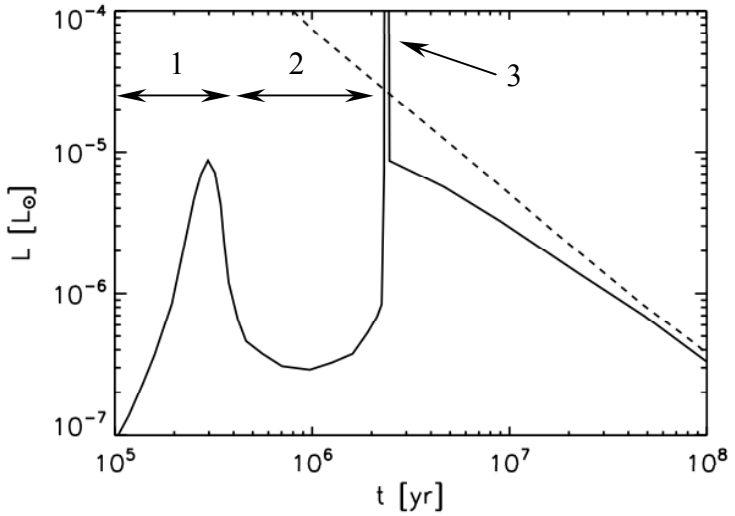

Figure 6: Luminosity versus time for a 2 M_J planet (Marley et al. 2007). The thick solid curve includes the effects of core accretion-gas capture. The planet is fully formed at 2.2 Myr. The dashed curve shows the simple cooling track of early "hot start" models. The full-width at half-maximum of the accretion luminosity spike is ~ 40,000 years. In reality, the spike is likely to be broader because of gradual accretion across the gap that the protoplanet forms. Numbers refer to the three phases: 1) sold accretion; 2) hydrodynamics gas accretion; and 3) run away gas accretion.

6. Conclusions

Direct detection and spectroscopic characterization of giant planets will open up new windows into planetary formation and new insights into the physics of planetary atmospheres. In the early part of the next decade, advanced AO coronagraphs will be sensitive to a broad range of self-luminous giant planets (1-10 M_J, 4-40 AU, 10-1000 Myr.) Investments in large-scale surveys and theoretical underpinnings will be needed to realize their potential. By the end of the decade, coronagraphs on a 25-40m GSMT or a dedicated space mission could allow spectroscopy of reflected light from mature gas or ice giant planets and perhaps allow imaging of planet formation in process.

7. References

Boss, A.P. 2002, ApJ, 576, 462

Burrows, A., Sudarsky, D.., Lunine, J. I. 2003 ApJ, 596, 587

Fortney, J. J., et al. 2008, ApJ 683, 1104

Gammie, C.F. 2001, ApJ, 553, 174

Goldreich, P., Lithwick, Y., & Sari, R. 2004, ARAA, 42, 549

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

Johnson, B.M., & Gammie, C.F. 2003, ApJ, 597, 131

Kalas, P. et al 2008 Science 322, 1345

Marley, M., et a.l 2007 Ap.J. 655, 541

Marois, C. et al 2008 Science 322, 1348

Marzari, F., & Weidenschilling, S.J. 2002, *Icarus*, 156, 5

Murray, N., Hansen, B., Holman, M., & Tremaine, S. 1998 *Science*, 279, 69

Oppenheimer, B., et al. 2008 Ap.J. 679, 1574

Pollack, J. B., et al. 1996, Icarus, 124, 62

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