PLANETARY PERTURBERS IN DEBRIS DISKS

MARC J. KUCHNER
Smithsonian Astrophysica1 Observatory

Abstract. Neptune dominates the dynamics of the Kuiper Belt. By examining images of debris disks around other stars, we may be able to infer what kinds of planets shape the outer edges of other planetary systems. The last few years have seen a burst of progress in the modeling of azimuthal structures in debris disks created by planetary perturbers; new models incorporate planets on substantially eccentric orbits. I review this recent progress in debris disk dynamics and discuss the Kuiper Belt as a key example.

1. Introduction

The extrasolar debris disks discovered so far are flawed Kuiper Belt analogs. They appear to have hundreds or thousands of times as much mass as the Kuiper Belt, and they orbit stars younger and/or more massive than the Sun (see the reviews by Backman and Paresce, 1993; Zuckerman, 2001). Though dust from our Kuiper Belt has not been detected, except possibly as a small component of the dust background in the inner solar system (Landgraf et al., 2002; Moro-Martin and Malhotra, 2003), extrasolar debris disks shine brightly in light reprocessed by dust grains.

However, we can add our knowledge of the Kuiper Belt to our general picture of debris disks, and we can use this general picture to inform our view of the Kuiper Belt. Extrasolar debris disks have begun to yield detailed images in the submillimeter, full of azimuthal structure (see the review by Wyatt in these proceedings). A massive planet perturbing these disks as Neptune perturbs the Kuiper Belt naturally creates rings with long-lived azimuthal structures (e.g., Roques et al., 1994; Lecavelier Des Etangs et al., 1996; Liou and Zook, 1999; Moro-Martin and Malhotra, 2002; Wilner et al., 2002; Quillen and Thorndike, 2002). Identifying these structures in extrasolar debris disks can teach us about extrasolar planets that otherwise would escape detection because of their long orbital periods.

The last few years have seen a burst of progress in the synthesis and interpretation of debris disk images via dynamical modeling, though we still have far to go. New models incorporate planets on substantially eccentric orbits; the azimuthal structures we see can indicate not only the presence of a perturbing planet, but also its mass and orbital eccentricity. I review this recent progress in the interpretation of azimuthal disk asymmetries and discuss the Kuiper Belt as a key example.

Earth, Moon and Planets **92:** 435–445, 2003.

2. Dust Trapped in Mean Motion Resonances

Collisions of KBOs can easily produce large quantities of dust (Stern, 1996; Yamamoto and Mukai, 1998), though we can not see dust from KBO collisions in our own solar system because the warmer zodiacal dust foreground obscures it (Teplitz et al., 1999). However, continuum emission from dust completely dominates images of extrasolar debris disks. This dust probably comes from collisions among extrasolar KBOs.

Unlike KBOs, dust grains feel strong forces from their interaction with starlight. Dust grains released at circumstellar distance r that are too large to be ejected by radiation pressure spiral into the star via Poynting-Robertson (P-R) drag (Robertson, 1937; Burns et al., 1979) in a short time:

$$T_{PR} = \frac{400}{\beta}\left(\frac{M_\odot}{M_*}\right)\left(\frac{r}{1AU}\right)^2 \text{years.} \tag{1}$$

where M_* is the mass of the star, and β is the ratio of the radiation pressure force on the grain to the stellar gravitational force on the grain. For a spherical particle with radius $s \geq 1\mu$m and density 2 g cm^{-3} orbiting a star with luminosity L_*,

$$\beta = \left(\frac{0.285\mu m}{s}\right)\left(\frac{L_*}{L_\odot}\right)\left(\frac{M_\odot}{M_*}\right), \tag{2}$$

though the effective particle radius, s is likely to be a few times smaller than the actual size of a realistic, non-spherical particle (Gustafson, 1994).

Since T_{PR} is so short, the battery of long-term dynamical effects that sculpts the distribution of KBO orbits (Duncan et al., 1995; Kuchner et al., 2002) does not directly affect dust particles. However, a planet can dramatically reshape the density of a dust cloud via mean motion resonances (MMRs), interactions that occur when the ratio of the particle's orbital period and the planet's orbital period approximates a ratio of small whole numbers (Gold, 1975). These resonances act on timescales $\sim \mu^{1/2}P$, where μ is the planet's mass divided by the star's mass, and P is the period of the planet's orbit. Dust spiralling inwards towards a planet encounters a series of exterior MMRs. As a particle approaches the planet from afar, it encounters stronger and stronger resonances, and has a better and better chance of becoming trapped. Dust trapped in MMRs creates density wave patterns; these patterns can indicate the nature of the perturbing planet.

Kuchner and Holman (2003) mapped the density wave patterns created by a list of important MMRs. By examining these patterns, they could determine qualitative features of debris disks subject to low-mass and high-mass perturbers on low-eccentricity and high-eccentricity orbits. Figure 1 shows four basic structures from Kuchner and Holman (2003) that probably represent the range of high-contrast resonant structures a planet with eccentricity $\leq$ 0.6 can create in a disk of dust

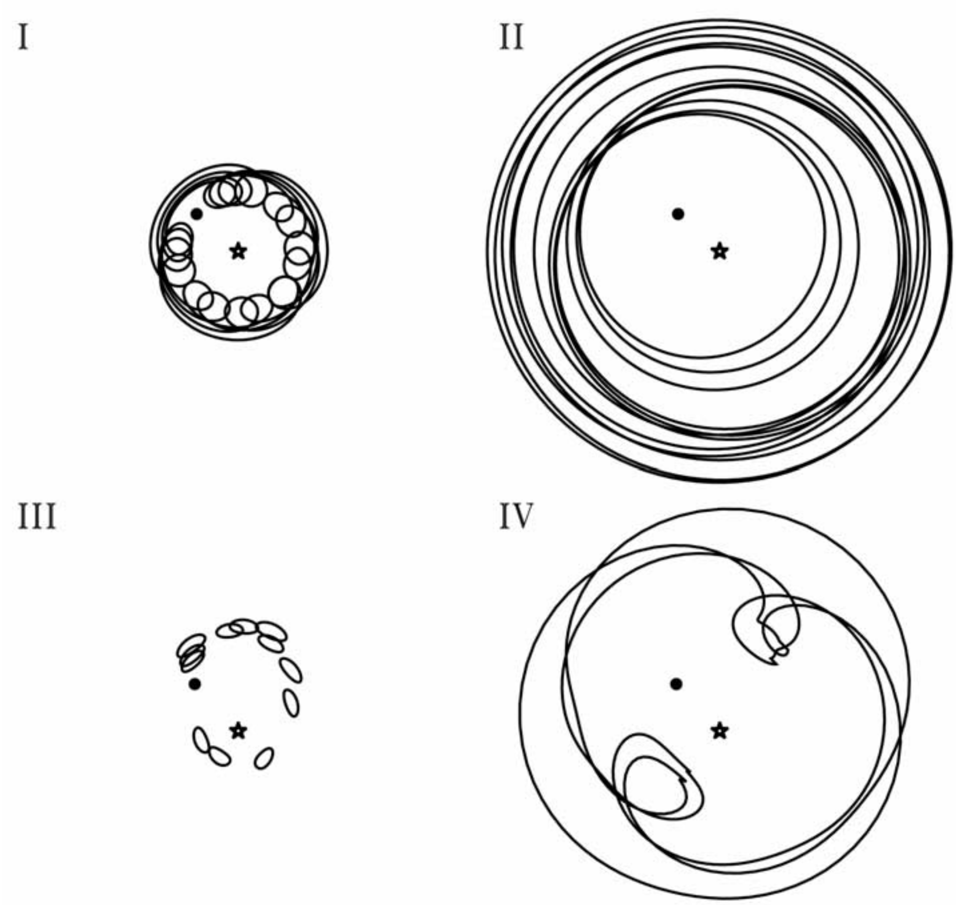

Figure 1. Four basic resonant structures: (I) low mass planet on a low eccentricity orbit, (II) high mass planet on a low eccentricity orbit, (III) low mass planet, moderate eccentricity orbit, and (IV) high mass planet, moderate eccentricity orbit. From Kuchner and Holman (2003).

released on low-eccentricity orbits: a ring with a gap at the location of the planet, a smooth ring, a blobby eccentric ring, and an offset ring plus a pair of clumps.

For dust spiralling in from a source much farther out than the planet, the spectrum of MMRs occupied by the dust mostly reflects the mass of the planet. The β of the dust particle also plays a role, but the structures shown in Figure 1 appear given particles with a wide range of β, only disappearing for the smallest particles, which are not generally detectable at submillimeter wavelengths. For particles approaching a low-mass planet (Cases I and III), the first resonances strong enough to trap substantial amounts of dust are the first-order MMRs, resonances of the form 2:1, 3:2, 4:3, etc. For more massive planets, all MMRs develop higher trapping probabilities, so particles approaching these planets become trapped sooner, in MMRs with longer orbital periods and larger semimajor axes. Planets as massive as Jupiter (Cases II and IV) trap dust predominantly in the $n : 1$ resonances, the lowest order resonances available at large semimajor axes.

When the planet's orbit is eccentric, the nature of each MMR changes as new terms appear in a harmonic expansion of the planet's gravitational potential (see, e.g., Murray and Dermott, 1999). Resonances with planets on circular orbits create density wave patterns that rotate with the same angular speed as the planet's orbital motion (Cases I and II). Resonances with planets on eccentric orbits create density wave patterns that change with the planet's orbital phase (Cases III and IV). This distinction can provide a critical test of the model (see Future Observations, below).

3. Simulations

Numerical simulations targeted at particular disks, including the Kuiper Belt, have explored some of the variety of structures a planet can produce in a cloud of non-interacting dust particles. They support the generalizations of Kuchner and Holman (2003) and reveal details glossed over in their approximations. Each numerical model has been presented merely as an example, not as a best fit, though sometimes even this limited approach suffices to constrain some of the orbital parameters of a putative perturbing planet.

3.1. Zodiacal Dust

The Earth traps a ring of zodiacal dust particles (Jackson and Zook, 1989; Dermott et al., 1994) seen by both the InfraRed Astronomical Satellite (Reach, 1991) and the Diffuse InfraRed Background Explorer (DIRBE) on the Cosmic Background Explorer (COBE) satellite (Reach et al., 1995). Dermott et al. (1994) and Marzari and Vanzani (1994) simulated this ring by numerically integrating the orbits of test particles subject to the gravity of the Sun and the Earth and radiation pressure and P-R drag. Dermott et al. (1994) modeled the density distribution of a steady state ring by dividing the plane of the Earth's orbit into boxes and recording how much time the particles spent in each box, making the approximation that any interesting structure co-rotates with the planet. The Earth's ring corresponds to Case I in Figure 1, a circular ring with a gap at the location of the planet. However, the Earth's low mass means that it traps relatively few particles; the ring represents a density enhancement of only a few percent. This effect would scarcely appear in an image of the solar system seen from afar.

3.2. Kuiper Belt Dust

Lion and Zook (1999) and Moro-Martin and Malhotra (2002, 2003) applied the technique pioneered by Dermott et al. (1994) to investigate the fate of dust generated in the Kuiper Belt. Figure 2 shows the surface density of one of the models computed by Moro-Martin and Malhotra (2002), using a symplectic integrator to

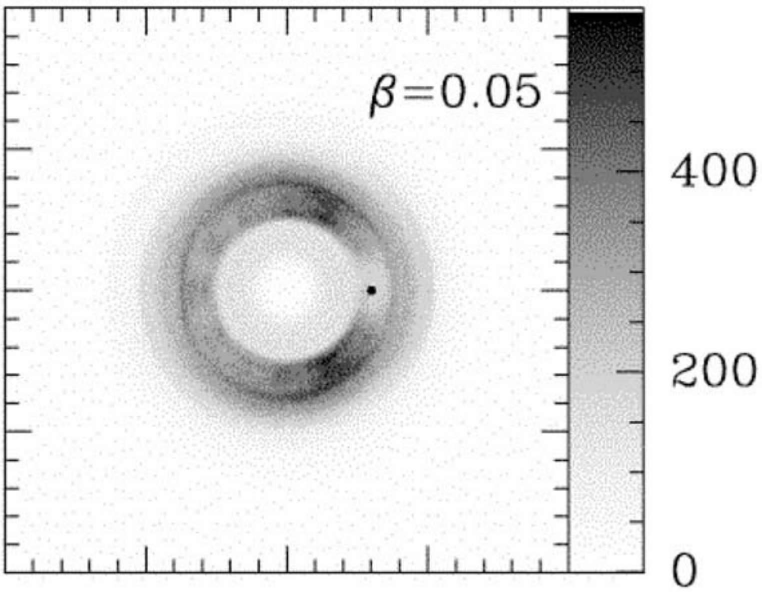

Figure 2. Simulation of KBO dust cloud surface density, an example of Case I. From Moro-Martin and Malhotra (2002),

follow the orbits of 300 particles with $\beta = 0.05$. Neptune's ring, like the Earth's ring, corresponds to Case I in Figure 1. The ring contains other azimuthal structures, besides the gap at the location of the planet, but these other structures depend strongly on the choice of β (Moro-Martin and Malhotra, 2002). The high-contrast ring created by Neptune would stand out in an image of the solar system seen from afar, provided the imaging telescope had the necessary dynamic range; even the best coronagraphs and interferometers have yet to obtain this dynamic range.

3.3. VEGA

The models of resonant rings in the solar system dust complex described above inspired attempts to explain structures in extrasolar debris disks via resonant trapping. Kuchner and Holman (2001) developed a technique of integrating the orbits of dust particles and recording stroboscopic histograms of the distribution of dust as a function of the planet's orbital phase, allowing them to model structures created by planets on substantially eccentric orbits. Wilner et al. (2002) used this technique, combined with a symplectic integration scheme, to explain submillimeter images of Vega that show two concentrations of emission resembling those in Figure 1, Case IV.

Like the lobes of the Case IV model, the concentrations in the Vega image are not co-linear with the star, and one is closer to the star than the other. Wilner et al. (2002) estimated that the perturbing planet has mass $\mu \approx 10^{-3}$ and eccentricity $e \approx 0.6$, and used the locations of the two knots of emission to infer the planet's

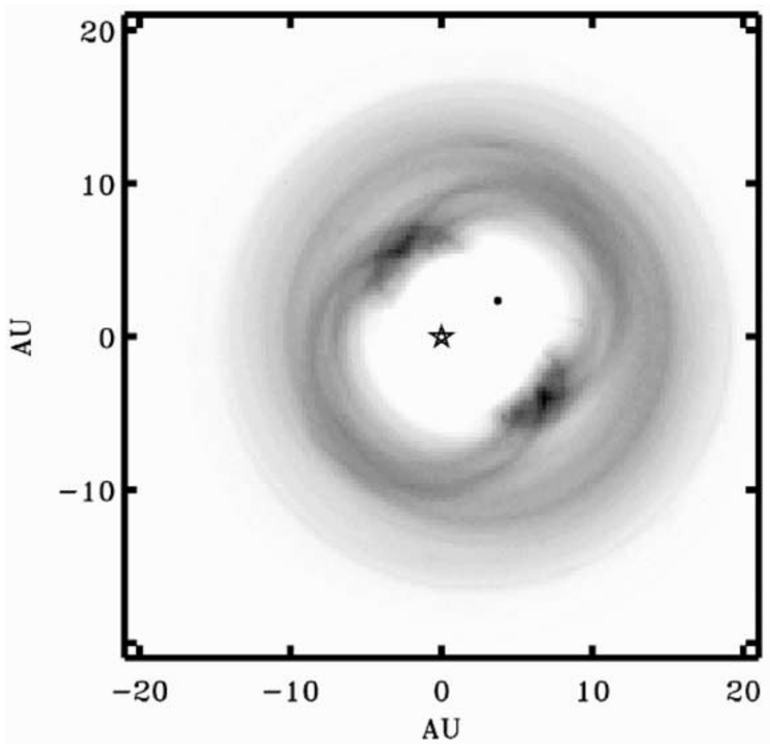

Figure 3. An example of Case IV; dust interacting with a few-Jupiter-mass planet on an orbit with eccentricity $e = 0.6$.

current location. Figure 3 shows a numerical example of Case IV, a simulation showing dust trapped in $n : 1$ resonances with a few-Jupiter-mass planet on an orbit with eccentricity $e = 0.6$; this is essentially the same model as the Wilner et al. (2002) model, except that in the calculation shown here, the dust is released far outside the planet.

Wyatt et al. (these proceedings) discuss a model for the Vega disk in which an outwardly migrating planet on a nearly circular orbit traps particles in its exterior 2:1 MMR. The asymmetric population of the split libration centers of this resonance generates an asymmetric twolobed distribution of particles – just as a migrating Neptune may trap KBOs preferentially into orbits librating about a particular center in its exterior 2:1 MMR (Chiang and Jordan, 2002). However, the Wyatt et al., model treats test particles, not dust particles that feel Poynting-Robertson drag and radiation pressure. These forces tend to destroy the subtle asymmetries of the 2:1 resonance, and drive particles into other nearby first order resonances, so that the dust in this model could easily resemble Case I. In any case, more observations of Vega are needed before we consider any model to be a good description of its disk.

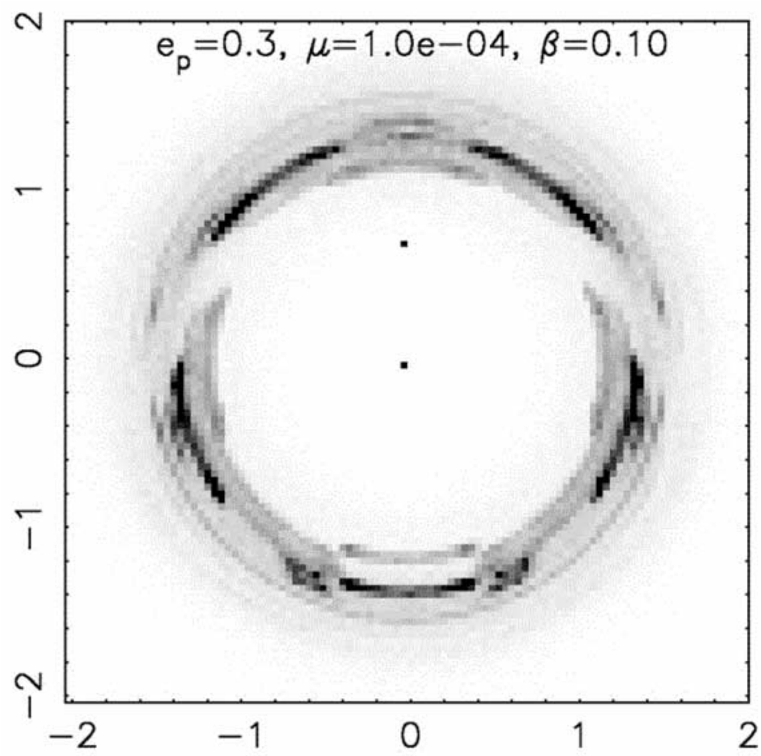

Figure 4. Model for the debris disk around e Eridani by Quillen and Thorndike (2002) – an example of Case III. This model assumes a roughly Neptune mass planet on an orbit with eccentricity $e = 0.3$.

3.4. ϵ ERIDANI

Submillimeter images of the nearby K2V star ϵ Eridani (Greaves et al., 1998) show a circumstellar ring with roughly four major concentrations of emission irregularly placed around it. At least one of these apparent concentrations is probably real, though some of the fainter ones could yet turn out to be noise. As Figure 1 shows, a Case III model (low-mass planet, moderate eccentricity orbit) would naturally explain the appearance of an eccentric dust ring with a few clumps of various concentrations. Quillen and Thorndike (2002) developed such a numerical model for the ϵ Eridani dust ring. They find that dust released just outside a planet with eccentricity 0.3 and mass $\mu = 10^{-4}$ becomes trapped in the 5:3 and the 3:2 MMRs with the planet, and forms a clumpy eccentric ring. Though dust trapped in these resonances probably forms relatively narrow rings, as shown in Figure 4, the large beam of the JCMT could easily blur such a narrow blobby ring into something resembling the Greaves et al. (1998) image, as Quillen and Thorndike (2002) illustrate.

Many other stars have debris disks, but most remain unresolved or marginally-resolved. Some well resolved disks, like those around β Pictoris and Fomalhaut, are hard to interpret because we view them roughly edge-on, though structure in these edge-on disk images may indicate the inclinations of planets they contain (Augereau et al., 2001; Wahhaj et al., 2003). Other disks that contain interesting azimuthal structure, like those around HR 4796A and HD 141569, probably represent a transitional stage between the massive gaseous disks commonly seen around Herbig Ae stars and replenished debris disks. Structure in such transitional disks may also reflect the presence of planets (Wyatt et al., 1999; but see also Klahr and Lin, 2001).

4. Discussion

4.1. Neptune on Eccentric Orbits

Precise-Doppler observations of nearby stars indicate that planets orbiting interior to 5 AU commonly have eccentric orbits (e.g., Marcy and Butler, 2000). The azimuthal structures we observe in extrasolar debris disks may be telling us that planets orbiting beyond 5 AU also commonly have eccentric orbits. The eccentricities of the precise-Doppler planets could conceivably stem from planet-planet interactions (Lin and Ida, 1997; Ford et al., 2001; Chiang et al., 2003) or from interactions with a massive disk (Goldreich and Sari, 2003; Ogilvie and Lubow, 2003). But since interactions between a planet and a protoplanetary disk generally cause planets to migrate inwards (Ward, 1986), planets orbiting at Kuiper Belt distances probably can not have acquired much eccentricity this way; planet-planet interactions are a more likely culprit.

Thommes et al. (1999) and Thommes et al. (2002) considered the possibility that Neptune formed near Jupiter and Saturn and got scattered by close encounters with these planets into a highly eccentric orbit. They invoke a massive primordial Kuiper Belt to circularize Neptune's orbit subsequent to the scattering, to match Neptune's orbit today. This scattered Neptune would have dynamically heated the Kuiper Belt, potentially explaining the presence of the high inclination KBO population – though the process would also alter any primordial low-inclination population. Whether or not a scattered Neptune helped shape the early solar system, other planetary systems probably do harbor Neptune mass planets scattered into high-eccentricity orbits. Debris disk images can potentially provide a census of these scattered Neptunes.

4.2. Collisions

The simulations described in Section 3 describe disks of non-interacting dust particles; they are good approximations for the solar system dust complex and no doubt for other low-mass debris disks, yet to be discovered. But they probably fail to capture all of the physics important to understanding the massive debris disks we observe around Vegalike stars. In these massive disks, a dust particle has a collision once every $\sim 10^3$ orbits, short enough that dust can not remain trapped in a resonance for a full P-R time. This effect probably alters the appearance of the disks from that predicted by the models.

Collisions can be both a sink and a source for dust particles (see Kenyon and Bromley, 2002 for a simulation of how collisions affect *radial* structure); perhaps some of the azimuthal structures we see in the more massive disks are short-lived clouds produced by recent collisions (e.g., Wyatt and Dent, 2002). Collisions must also change the orbits of the particles that survive them, at least by damping their orbital energy, on average. Dust particles created by collisions do not continue on the same orbits as their parent bodies; radiation pressure immediately changes the effective central potential the grains orbit by an amount that can be comparable to the width of a MMR for grains with large β, and in general, the physics of high-speed collisions of icy bodies remains poorly understood. As a starting point, future models should consider in depth how particles with a range of βs interact with planets. They should also explore in more detail how the cloud structure reflects the initial dust orbits.

4.3. FUTURE OBSERVATIONS

The Kuiper Belt, or rather, the solar system small-body complex, is the least massive debris disk known. We can point to the massive debris disks we have found so far and visualize a younger Kuiper Belt, before collisions ground most of it to dust (Stern and Colwell, 1997). But soon, sensitive infrared telescopes like SIRTF and JWST and submillimeter observatories like SMA and ALMA should find less massive debris disks, more like today's Kuiper Belt.

Besides finding new disks, future observations can test the models we have discussed by measuring how known debris disks evolve with time. Case I and II disks should appear to rotate as solid bodies. Case III disks contain a few overlapping rings that rotate at a different rates, so their images should show dust concentrations apparently created and destroyed as the rings rotate through one another. Case IV disks should appear to rotate as solid bodies, rotating around a point along the apsidal line of the planet's orbit, not around the star, at half the orbital frequency of the perturbing planet. However, we may need to wait another 10 years before we can begin to measure the time evolution of debris disks, and even longer before we can distinguish one model from another.

We have acquired some understanding of azimuthal structures in disks of non-interacting dust particles with one planet. With any luck we will one day have images of many faint, collisionless disks to which we can apply these models in complete confidence. But in the meantime, we need to work harder to explain the complicated massive disks we have already imaged.

Acknowledgements

Thanks to Ann Bragg, Matthew Holman, Renu Malhotra, Alice Quillen, Wes Traub, and Mark Wyatt for contributions and proofreading.

This work was performed in part under contract with the Jet Propulsion Laboratory (JPL) through the Michelson Fellowship program funded by NASA as an element of the Planet Finder Program. JPL is managed for NASA by the California Institute of Technology.

References

Augereau, J. C., Nelson, R. P., Lagrange, A. M., Papaloizou, J. C. B., and Mouillet, D.: 2001, *A&A* **370**, 447.

Aumann, H. H., Gillett, F. C., Beichman, C. A., de Jong, T., Houck, J. R., Low, F. J., Neugebauer, G., Walker, R. C., and Wesselius, P. R.: 1984, *Astrophys. J.* **278**, L23.

Backman, D. E. and Paresce, F.: 1993, in E. H. Levy and J. I. Lunine (eds.), *Protostars and Planets III*, University of Arizona Press, Tucson.

Burns, J. A., Lamy, P., and Soter, S. 1979, *Icarus* **40**, 1.

Chiang, E. I., Fischer, D., and Thommes, E.: 2002, *Astrophys. J.* **564**, L105.

Chiang, E. I. and Jordan, A.: 2002, *Astrophys. J.* **124**, 3430.

Dermott, S. F., Jayaraman, S., Xu, Y. L., Gustafson, B. A. S., and Liou, J.-C.: 1994, *Nature* **369**, 719.

Duncan, M. J., Levison, H. F., and Budd, S. M.: 1995, *Astronom. J.* **110**, 3073.

Ford, E. B., Havlickova, M., and Rasio, F. A.: 2001, *Icarus* **150**, 303.

Gold, T.: 1975, *Icarus* **25**, 489.

Goldreich, P. and Sari, R.: 2003, *Astrophys. J.* **585**, 1024.

Greaves et al.: 1998, *Astrophys. J.* **506**, L133.

Gustafson, B. A. S.: 1994, *Ann. Rev. Earth & Plan. Sci.* **22**, 553.

Holland, W. S., Greaves, J. S., Zuckerman, B., Webb, R. A., McCarthy, C., Coulson, I. M., Walther, D. M., Dent, W. R. F., Gear, W. K., Robson, I.: 1998, *Nature* **392**, 788.

Jackson, A. A. and Zook, H. A.: 1989, *Nature* **337**, 629.

Kenyon, S. J. and Bromley, B. C.: 2002, *Astrophys. J.* **577**, L35.

Klahr, H. Hubertus and Lin, D. N. C.: 2001, *Astrophy. J.* **554**, 1095.

Kuchner, M. J. and Holman, M.: 2001, presented at the December 2001 Division of Planetary Sciences meeting.

Kuchner, M. J., Brown, M. E., and Holman, M. J.: 2002, *Astronom. J.* **124**, 1221.

Kuchner, M. J. and Holman, M. J.: 2003, *Astrophys. J.* **588**, 1110, astroph/0209261.

Landgraf, M., Liou, J.-C., Zook, H. A., and Grijn, E.: 2002, *Astronom. J.* **123**, 2857.

Lecavelier Des Etangs, A., Scholl, H., Roques, F., Sicardy, B., and Vidal-Madjar, A.: 1996, *Icarus* **123**, 168.

Lin, D. N. C. and Ida, S.: 1997, *Astrophys. J.* **477**, 781.

Liou, J.-C. and Zook, H. A.: 1999, *Astronom. J.* **118**, 580.

Marcy, G. W. and Butler, R. P.: 2000, *PASF* **768**, 137.

Marzari, F. and Vanzani, V.: 1994, *A&A* **283**, 275.

Moro-Martin, A. and Malhotra, R.: 2002, *Astronom. J.* **124**, 2305.

Moro-Martin, A. and Malhotra, R.: 2003, *Astronom. J.* **125**, 2255.

Murray, C. D. and Dermott, S. F.: 1999, *Solar System Dynamics*, Cambridge University Press, New York.

Ogilvie, G. I. and Lubow, S. H.: 2003, *Astrophys. J.* **587**, 398.

Quillen, A. C. and Thorndike, S.: 2002, *Astrophys. J.* **578**, L149.
Reach, W. T.: 1991, *Astrophys. J.* **369**, 529.
Reach, W. T., Franz, B. A., Weiland, J. L., Hauser, M. G., Kelsall, T. N., Wright, E. L., Rawley, G., Stemwedel, S. W., and Spiesman, W. J.: 1995, *Nature* **374**, 521.
Robertson, H. P.: 1937, *MNRAS* **97**, 423.
Roques, F., Scholl, H., Sicardy, B., and Smith, B. A.: 1994, *Icarus* **108**, 37.
Stern, S. A.: 1996, *A&A* **310**, 999.
Stern, S. A. and Colwell, J. E.: 1997, *Astronom. J.* **114**, 841.
Teplitz, V. L., Stern, S. A., Anderson, J. D., Rosenbaum, D., Scalise, R. J., and Wentzler, P.: 1999, *Astrophys. J.* **516**, 425.
Thommes, E. W., Duncan, M. J., and Levison, H. F.: 1999, *Nature* **402**, 635.
Thommes, E. W., Duncan, M. J., and Levison, H. F.: 2002, *Astronom. J.* **123**, 2862.
Wahhaj, Z., Koerner, D. W., Ressler, M. E., Werner, M. W., Backman, D. E., and Sargent, A. I.: 2003, *Astrophys. J.* **584**, L27.
Ward, W. R.: 1986, *Icarus* **67**, 16.
Wilner, D. J., Holman, M. J., Kuchner, M. J., and Ho, P. T. P.: 2002, *Astrophys. J.* **569**, L115.
Wyatt, M. C. and Dent, W. R. F.: 2002, *MNRAS* **334**, 589.
Wyatt, M. C., Dermott, S. F., Telesco, C. M., Fisher, R. S., Grogan, K., Holmes, E. K., and Pina, R. K.: 1999, *Astrophys. J.* **527**, 918.
Yamamoto, S. and Mukai, T.: 1998, *A&A* **329**, 785.
Zuckerman, B.: 2001, *Ann. Rev. Astron. Astrophys* **39**, 549.