Signatures of Catastrophic Planetesimal Disruptions in the β Pictoris Debris Disk

†Thomas J. J. Kehoe,[1] Stanley F. Dermott,[1] Charles M. Telesco,[1] R. Scott Fisher,[2] Ludmilla Kolokolova,[1] Steven J. Novotny,[1] and Mark C. Wyatt[3]

[1]Department of Astronomy, University of Florida, Gainesville, Florida 32611, USA
[2]Gemini Observatory Northern Operations Center, Hawaii 96720, USA
[3]UK Astronomy Technology Centre, Royal Observatory, Edinburgh EH9 3HJ, UK

†E-mail: kehoe@astro.ufl.edu

Abstract

We investigate the potential for the catastrophic collisional disruption of planetesimals in the β Pictoris debris disk to account for some of the structure observed in the disk, such as the marked brightness asymmetry between the NE and SW lobes and the existence of rings of material. We report preliminary results from numerical simulations that reveal the creation of transient structure in the disk following the release of a power-law size distribution of particles due to the breakup of a planetesimal. The effect of radiation pressure on the particles released causes some of them to be ejected from the system, and we consider the possibility that these particles are the source of the collimated stream of interstellar particles detected by the Advanced Meteor Orbit Radar. Those particles that remain in bound orbits rapidly generate a spiral of material that gradually fills out to form an asymmetric disk that is oriented such that the periastron of the particles' orbits lies at the point of the planetesimal's breakup. This disk will eventually decay inward under the effect of Poynting-Robertson drag. We consider the effect of a variety of different parameters on the disk structure generated in these simulations.

2nd TPF/Darwin International Conference, San Diego CA, 26–29 July 2004

1 Introduction

- Debris disks are circumstellar disks that are comprised of particles that are not primordial but are continually replenished by the erosion of their planetesimal populations.

- Recent high-resolution images of the β Pictoris debris disk at multiple mid-IR wavelengths (Telesco et al., 2004) show a marked brightness asymmetry between the NE and SW lobes of the central disk ($\lesssim 200$ AU from the star), in agreement with previous observations obtained at $\sim 12\,\mu$m (Lagage and Pantin, 1994; Pantin et al., 1997; Weinberger et al., 2003).

- The objective of this work is to explore the dynamical behavior of particles in the debris disk of β Pictoris. In particular, we investigate the effect of radiation pressure, acting on a population of particles that were released following the collisional disruption of a large ($\gtrsim 1{,}000$ km diameter) planetesimal, as a mechanism for generating the observed asymmetry in the central disk.

- Collisional disruptions of planetesimals in debris disks has previously been discussed by, among others, Wyatt and Dent (2002) and Wyatt (2003) in the case of the Fomalhaut and Vega debris disks respectively, and in a general planet formation context by Kenyon and Bromley (2002; 2003; 2004). The distribution of dust in β Pictoris under the influence of radiation pressure has been discussed by, for example, Lecavelier des Etangs et al. (1996). Detailed modeling of the collisional evolution of the inner disk of β Pictoris (< 10 AU) has been performed by Thébault et al. (2003).

2 Dynamical Simulations

- Dust particles were assumed to be composed of a porous mixture of silicates, organics, carbon, and ice in cosmic abundances, and were given a power-law size distribution between $7\,\mu$m (shown in blue) and $20\,\mu$m (shown in red) in diameter, with a power-law index of -3. The minimum particle size of the distribution was chosen to be close to the "blow-out" limit, the threshold below which particles would be ejected from the β Pictoris system due to the effect of radiation pressure, in this case, $7\,\mu$m in diameter (see, for example, Artymowicz, 1988).

- 10,000 particles were released from a disrupted planetesimal and were given an isotropic velocity distribution relative to the planetesimal, with ejection speeds distributed in a Gaussian fashion with a mean of zero and a standard deviation given by the escape velocity of the planetesimal.

- Various physical properties for the planetesimal were chosen, in order to approximate several different planetesimal analogs. In the example results shown here in Figs. 1–3, a planetesimal analog to Quaoar (a large Kuiper Belt Object) was used and was initially placed on a circular, non-inclined orbit with a semimajor axis of 50 AU. A smaller Kuiper Belt Object (KBO) analog and a Pluto analog were also investigated.

2nd TPF/Darwin International Conference, San Diego CA, 26–29 July 2004

- In these preliminary simulations, the dust particles were treated as massless bodies and evolved as a simple 2-body problem with the central star under the effects of radiation pressure and Poynting-Robertson (P-R) drag alone, using a specially designed numerical integration code (Kehoe et al., 2003). The potential effect of gravitational perturbations by a putative planetary system on the particles was not modeled in these simulations. In addition, the system was assumed to be collisionless and gas drag (see Artymowicz these proceedings) was ignored.

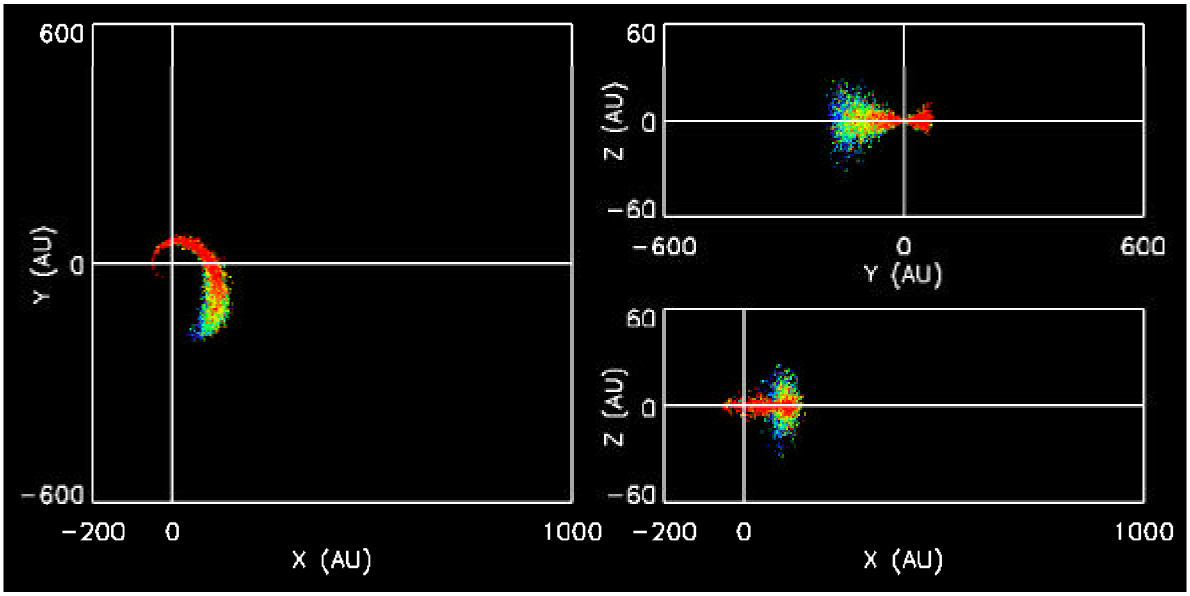
3 Results

- Figures 1–3 show a sequence of time frames illustrating the dynamical behavior of particles in the debris disk of β Pictoris that were assumed to be released during the catastrophic collisional disruption of a Quaoar (large KBO) analog. Following their release, the orbits of the particles are immediately affected by radiation pressure, resulting in a large trail of material arcing rapidly away from the central star (Fig. 1: top panel). This trail of material quickly wraps around itself, within a few orbital periods of the disrupted planetesimal, to form a spiral of material in the disk (Fig. 1: bottom panel). However, it is important to realize that each particle released follows an orbit with a slightly different semimajor axis, that is determined by radiation pressure and the escape velocity from the disrupted planetesimal. The points displayed in the figures are not tracing a single orbit but represent a snapshot of the particles on each orbit.

- This spiral of material gradually disperses to start filling out a disk from the inside out (i.e., from smaller semimajor axes with shorter periods to larger semimajor axes with longer periods), as shown in Fig. 2. This asymmetric disk is oriented such that it is extended in the direction of the particle distribution apocenters and truncated in the direction of their pericenters. The pericenters of the particles released coincide with the location of the planetesimal disruption and the effect of radiation pressure causes the semimajor axes and eccentricities of their orbits to instantaneously increase from that of their progenitor body upon release.

- After several tens to hundreds of orbital periods of the disrupted planetesimal, the dust particles are sufficiently dispersed around their independent orbits to fill out the entire disk (Fig. 3).

- The main difference between these results and those obtained for the KBO and Pluto analogs is a result of the different escape velocities of these planetesimals: in the case of the Pluto analog, the particles are more dispersed initially and the distribution of particles becomes disk-like more rapidly; whereas for the KBO analog, the particles trace out a well-defined spiral structure for longer.



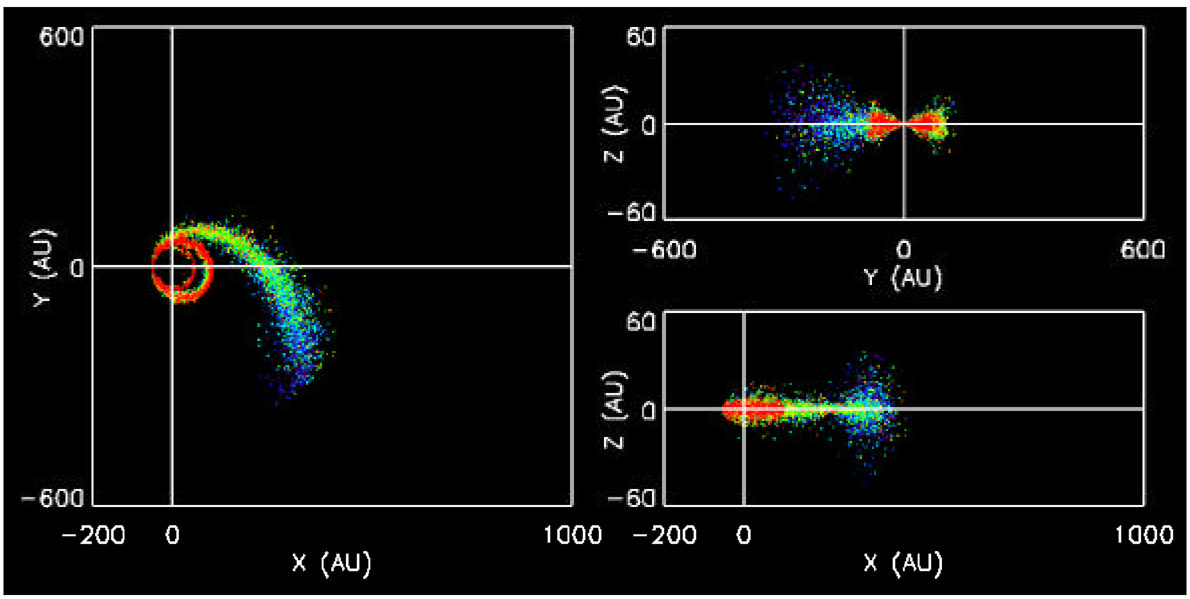
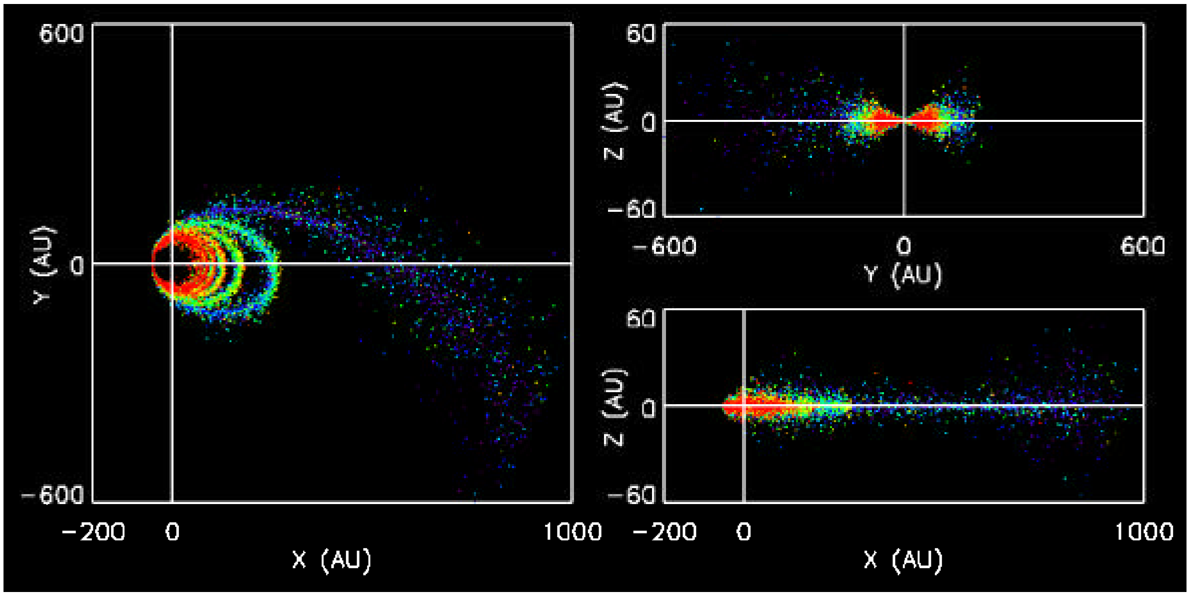


Fig. 1. Sequence of time frames illustrating the dynamical behavior of particles in the debris disk of β Pictoris that were assumed to be released during the catastrophic collisional disruption of a large ($\gtrsim$ 1,000 km diameter) planetesimal, which was initially placed on a circular, non-inclined orbit with a semimajor axis of 50 AU. The time frames above show the projected distributions of the particles in a three-dimensional Cartesian coordinate frame centered on β Pictoris after 1 (top panel) and 3 (bottom panel) orbital periods of the disrupted planetesimal.



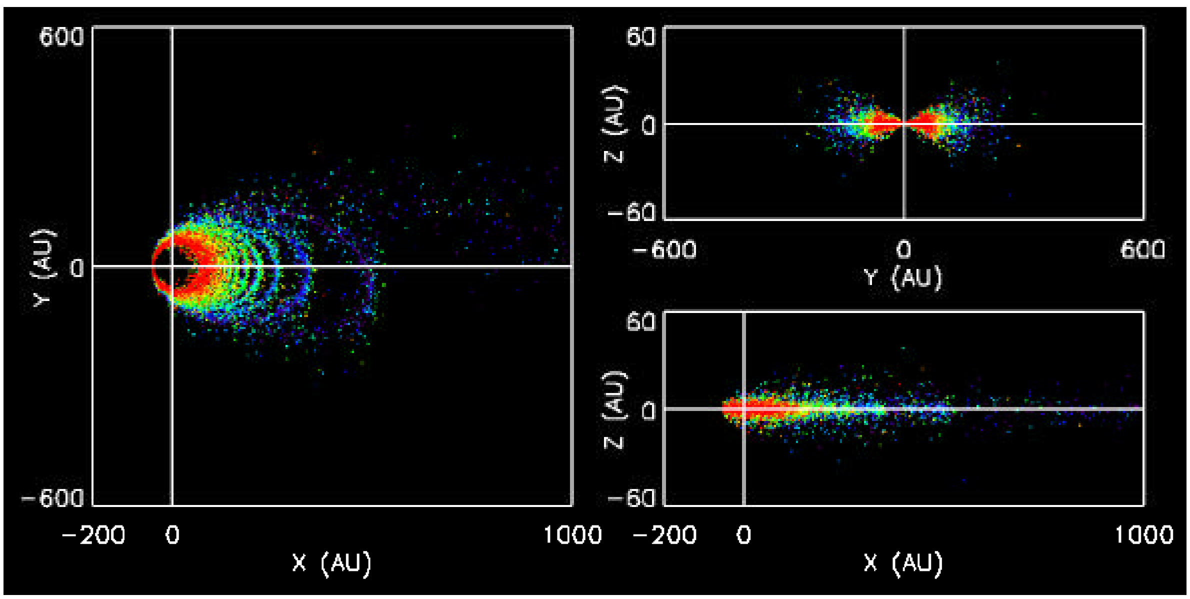


Fig. 2. As for Fig. 1 but showing the distributions of the particles after 10 (top panel) and 25 (bottom panel) orbital periods of the disrupted planetesimal.

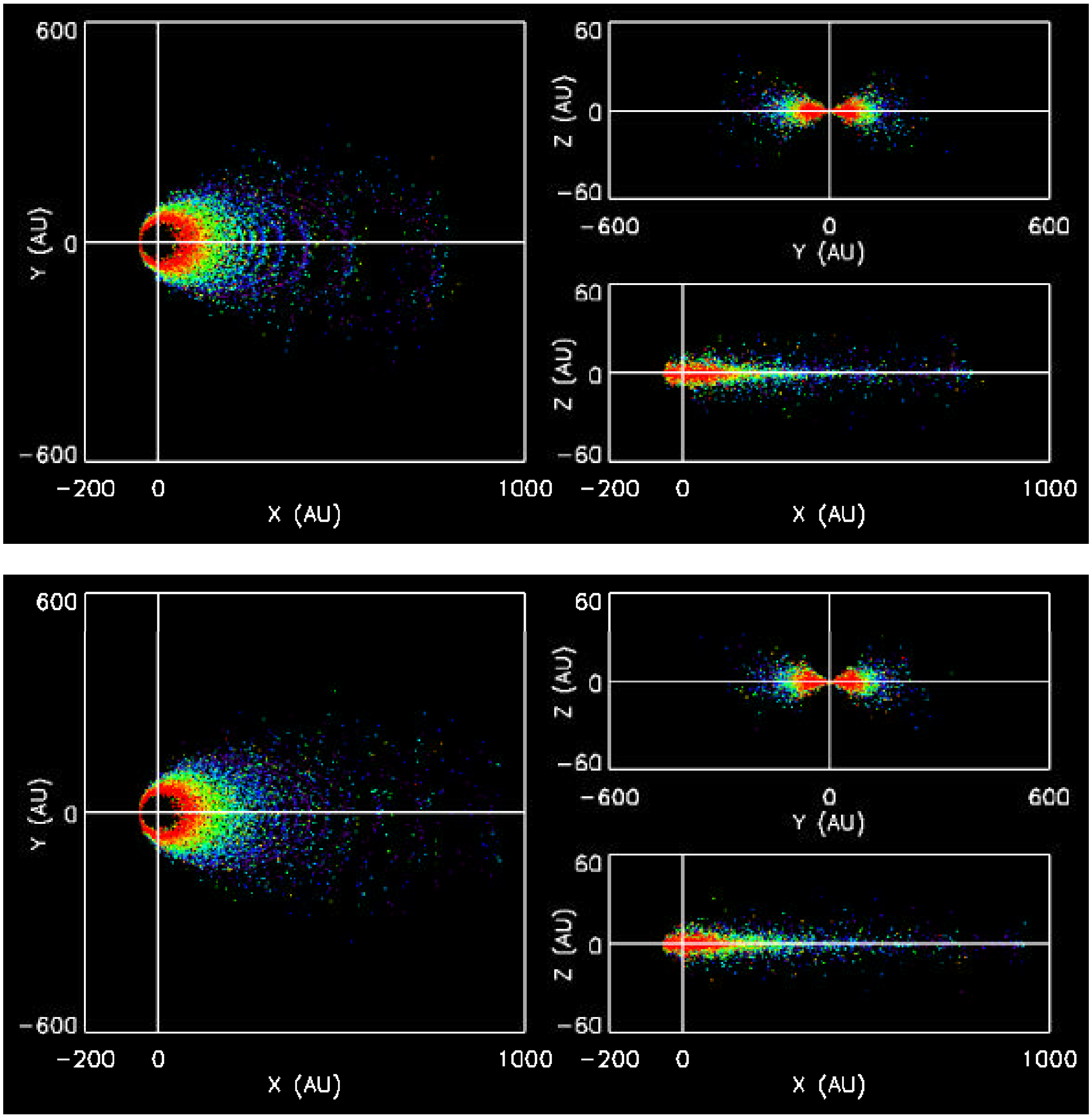


Fig. 3. As for Fig. 1 but showing the distributions of the particles after 45 (top panel) and 100 (bottom panel) orbital periods of the disrupted planetesimal.

4. Discussion

- Particles released following the collisional disruption of a large ($\gtrsim 1{,}000$ km diameter) planetesimal rapidly form an asymmetric disk of material (within ~ 100 orbital periods of the progenitor body). This disk is oriented such that it is extended in the direction of the particle's apocenters and truncated in the direction of their pericenters.

- Note that although material closer to the central star disperses rapidly to form a disk, material farther away from the central star retains its spiral form for longer (Fig. 2). Does this explain the ring structure observed at optical wavelengths in the outer disk of β Pictoris (Kalas et al., 2000)? This structure has previously been interpreted as being caused by the tidal influence of a passing star (Kalas et al., 2000; Larwood and Kalas, 2001). The effect of a stellar-flyby has also been suggested as a mechanism for causing the asymmetry observed in optical imaging of the outer disk (Kalas and Jewitt, 1995).

- Some of the particles that are created following the collisional disruption of a planetesimal are ejected from the β Pictoris disk under the effect of radiation pressure. Is this the mechanism responsible for generating the stream of interstellar particles detected by the Advanced Meteor Orbit Radar (AMOR) based in New Zealand (Baggaley, 2000; Krivov et al., 2004)?

- Production of a significant cross-sectional area of material as a result of the catastrophic breakup of a large planetesimal may cause a debris disk to temporarily flare into visibility (Dermott et al., 2002; 2004). The injection of this fresh collisional debris into the disk may subsequently initiate a collisional cascade with the material already present that would further enhance this effect. Transient stochastic processes occurring in debris disks, such as collisional events, have been proposed as a possible explanation for Spitzer MIPS data that indicate a range of infrared excesses are observed for stars of a similar age (see Rieke these proceedings); and also as a possible mechanism for generating the observed NE/SW lobe asymmetry in the central disk of β Pictoris (Telesco et al., 2004).

- Eventually, the orbits of particles that remain bound will decay into the central star under the influence of P-R drag, at a rate determined by particle size (Wyatt and Whipple, 1950). The structure created by the effect of radiation pressure on collisionally generated debris is therefore transient. However, as the particles spiral inwards, gravitational perturbations by a planetary system would impose longer-term structure on the remaining disk of particles (see, for example, Ozernoy et al., 2000).

References

Artymowicz P. (1988) Radiation pressure forces on particles in the Beta Pictoris system. *Astrophys. J.*, 335, L79–L82.

Baggaley W. J. (2000) Advanced Meteor Orbit Radar observations of interstellar meteoroids. *J. Geophys. Res.*, 105, 10353–10362.

Dermott S. F., Kehoe T. J. J., Durda D. D., Grogan K., and Nesvorný D. (2002) Recent rubble-pile origin of asteroidal solar system dust bands and asteroidal interplanetary dust particles. In *Asteroids, Comets, and Meteors 2002*, ESA SP-500 (B. Warmbein, ed.), pp. 319–322. ESA Publications Division, Noordwijk.

Dermott S. F., Telesco C., Kehoe T., Kolokolova L., Mahoney-Hopping L., Novotny S., Wyatt M., Zolensky M. (2004) The origin and dynamics of interplanetary dust particles with application to the solar system dust bands and the structure of the Beta Pictoris debris disk. *35th Annual Meeting of the American Astronomical Society Division on Dynamical Astronomy*, abstract 01.06.

Kalas P. and Jewitt D. (1995) Asymmetries in the Beta Pictoris dust disk. *Astron. J.*, 110, 794–804.

Kalas P., Larwood J., Smith B. A., and Schultz A. (2000) Rings in the planetesimal disk of β Pictoris. *Astrophys. J.*, 530, L133–L137.

Kehoe T. J. J., Murray C. D., and Porco C. C. (2003) A dissipative mapping technique for the N-body problem incorporating radiation pressure, Poynting-Robertson drag, and solar-wind drag. *Astron. J.*, 126, 3108–3121.

Kenyon S. J. and Bromley B. C. (2002) Dusty rings: Signposts of recent planet formation. *Astrophys. J.*, 577, L35–L38.

Kenyon S. J. and Bromley B. C. (2003) Collisional cascades in planetesimal disks. II. Embedded planets. *Astron. J.*, 127, 513–530.

Kenyon S. J. and Bromley B. C. (2004) Detecting the dusty debris of terrestrial planet formation. *Astrophys. J.*, 602, L133–L136.

Krivov A. V., Krivova N. A., Solanki S. K., and Titov V. B. (2004) Towards understanding the β Pictoris dust stream. *Astron. Astrophys.*, 417, 341–352.

Lagage P. O. and Pantin E. (1994) Dust depletion in the inner disk of β Pictoris as a possible indicator of planets. *Nature*, 369, 628–630.

Larwood J. D. and Kalas P. G. (2001) Close stellar encounters with planetesimal discs: the dynamics of asymmetry in the β Pictoris system. *Mon. Not. R. Astron. Soc.*, 323, 402–416.

Lecavelier des Etangs A., Vidal-Madjar A., and Ferlet R. (1996) Dust distribution in disks supplied by small bodies: Is the β Pictoris disk a gigantic multi-cometary tail? *Astron. Astrophys.*, 307, 542–550.

Ozernoy L. M., Gorkavyi N. N., Mather J. C., Taidakova T. A. (2000) Signatures of exosolar planets in dust debris disks. *Astrophys. J.*, 537, L147–L151.

Pantin E., Lagage P. O., and Artymowicz P. (1997) Mid-infrared images and models of the β Pictoris dust disk. *Astron. Astrophys.*, 327, 1123–1136.

Telesco C. M., Fisher R. S., Wyatt M. C., Kehoe T. J. J., Dermott S. F., Novotny S., Mariñas N., Radomski J. T., Packham C. C., DeBuizer J., Hayward T. (2004) Catastrophic planetesimal breakup in the central disk of β Pictoris. *Nature*, in preparation.

Thébault P., Augereau J. C., and Beust H. (2003) Dust production from collisions in extrasolar planetary systems: The inner β Pictoris disc. *Astron. Astrophys.*, 408, 775–788.

Weinberger A. J., Becklin E. E., and Zuckerman, B. (2003) The first spatially resolved mid-infrared spectroscopy of β Pictoris. *Astrophys. J.*, 584, L33–L37.

Wyatt M. C. (2003) Resonant trapping of planetesimals by planet migration: Debris disk clumps and Vega's similarity to the solar system. *Astrophys. J.*, 598, 1321–1340.

Wyatt M. C. and Dent W. R. F. (2002) Collisional processes in extrasolar planetesimal discs — dust clumps in Fomalhaut's debris disc. *Mon. Not. R. Astron. Soc.*, 334, 589–607.

Wyatt S. P. Jr. and Whipple F. L. (1950) The Poynting-Robertson effect on meteor orbits. *Astrophys. J.*, 111, 134–141.