NASA ADP grant NAG5-9280, *A Global, Multi-Waveband Model for the Zodiacal Cloud*: Final Report

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Objectives

This recently completed three-year project was undertaken by the PI at the University of Florida, NASA Goddard and JPL, and by the Co-I and Collaborator at the University of Florida. The funding was used to support a continuation of research conducted at the University of Florida over the last decade which focuses on the dynamics of dust particles in the interplanetary environment. The main objectives of this proposal were:

- To produce improved dynamical models of the zodiacal cloud by performing numerical simulations of the orbital evolution of asteroidal and cometary dust particles.
- To provide visualizations of the results using our visualization software package, SIMUL, simulating the viewing geometries of IRAS and COBE and comparing the model results with archived data.
- To use the results to provide a more accurate model of the brightness distribution of the zodiacal cloud than existing empirical models.

  In addition, our dynamical approach can provide insight into fundamental properties of the cloud, including but not limited to the total mass and surface area of dust, the size-frequency distribution of dust, and the relative contributions of asteroidal and cometary material. The model can also be used to provide constraints on trace signals from other sources, such as dust associated with the "Plutinos", objects captured in the 2:3 resonance with Neptune.

Accomplishments

- We now have a better appreciation for the relative importance of the sources that feed the cloud: as a result of our detailed models of the Solar System dust bands we believe that the cloud is predominantly asteroidal. Perhaps as much as 30% of zodiacal dust resides in the asteroidal dust bands alone (Figure 1), meaning that perhaps 90% of zodiacal dust originates in the asteroid belt and 10% comes from comets (Grogan et al. 2001, Dermott et al. 2003)
- The dust band models also provide an estimate for the size-frequency distribution of dust particles in the main-belt, the result indicating that the dust band emission is dominated by large particles, greater than 100 microns in diameter (Figure 2, Grogan et al. 2001)

- We have shown how the orbital distribution of dust particles changes markedly over their dynamical lifetime, and that the action of secular resonances at the inner edge of the asteroid belt disperses low inclination, low eccentricity dust particles into the asteroidal background, making them appear more 'comet-like' (Figure 3, Grogan et al. 2001; Kehoe et al. 2002a). This also has implications for the origin of extraterrestrial material accreted by Earth, and how it varies over time (Dermott et al. 2001; Kortenkamp et al. 2001)
- We have shown how the stocastic nature of asteroidal collisions results in large-scale injections of collisional debris into the zodiacal cloud, with the result that the optical depth of the cloud can 'spike' by orders of magnitude on numerous occasions over its lifetime (Figure 4, Grogan et al. 2001; Dermott et al. 2001)
- We have provided constraints for the structure and detectabilty of dust particles trapped in a 'Plutino disk', material captured in the 2:3 resonance with Neptune (Holmes et al. 2003)
- We have further demonstrated how the planetary system imposes structure on the zodiacal cloud by warping its plane of symmetry, and by offsetting the cloud from the Sun (Dermott et al. 2001, Dermott et al. 2003). This information is directly applicable to the understanding of structure in Vega-type debris disks, and has led to the success of our subsequent NASA proposals (see Follow-on grants section).

Follow-on grants

Many of the results of this project, while directly applicable to the zodiacal cloud, are also relevant to the study of debris disks around other stars. A cornerstone of NASA's Origins program is an understanding of the origin and evolution of planetary systems. Over the next decade observations from a variety of observing platforms, including SIRTF, Keck Interferometer, SIM, JWST, leading to Terrestrial Planet Finder will allow us to detect extrasolar planets, and make meaningful estimates on how common these planetary systems might be. However, zodiacal emission in both our own system and in the target system may have the potential to seriously impact the chances for success of these missions. Addressing these concerns along with further studies of the zodiacal cloud are the subject of three follow-on grants, one already funded and two more which have been submitted this year.

Funded

- NASA Origins of Solar Systems, 2003-2005, "Dynamical Modeling and Detectability of Debris Disk Structure - Laying the Groundwork for Terrestrial Planet Finder", PI Dr. Keith Grogan

Submitted

- NASA Terrestrial Planet Finder Foundation Science, 2004-2006, "The Nature of Asteroidal and Cometary Exo-zodiacal Clouds", PI Dr. Keith Grogan
- NASA Astrophysics Data Analysis Program, 2004-2006, "MSX Constraints on the Origin and Structure of the Zodiacal Dust Bands", PI Dr. Keith Grogan

Publications and Presentations Relevant to this Award

Book Chapters

Dermott S. F., Durda D. D., Grogan K., and Kehoe T. J. J. (2003) Asteroidal dust. In *Asteroids III* (W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, eds.), pp. 423–442. Univ. Arizona Press, Tucson.

Dermott S. F., Grogan K., Durda D. D., Jayaraman S., Kehoe T. J. J., Kortenkamp S. J., and Wyatt M. C. (2001) Orbital evolution of interplanetary dust. In *Interplanetary Dust* (E. Grün, B. Å. S. Gustafson, S. F. Dermott, and H. Fechtig, eds.), pp. 569–639. Springer-Verlag, Berlin.

Kortenkamp S. J., Dermott S. F., Fogle D., and Grogan K. (2001) Sources and orbital evolution of interplanetary dust accreted by Earth. In *Accretion of Extraterrestrial Matter Throughout Earth's History* (B. Peucker-Ehrenbrink and B. Schmitz, eds.), pp. 13–30. Kluwer Acad./Plenum Publ., New York.

Journal Articles

Grogan K., Dermott S. F., and Durda D. D. (2001) The size-frequency distribution of the zodiacal cloud: evidence from the solar system dust bands. *Icarus*, 152, 251–267.

Holmes, E. K., Dermott, S. F., Gustafson, B. Å. S. and Grogan, K. (2003) Resonant Structure in the Kuiper Disk: An Asymmetric Plutino Disk. *Ap. J.*, 597, 1211-1236.

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.*, in press.

Refereed Conference Papers

Dermott S. F., Kehoe T. J. J., Durda D. D., Grogan K., and D. Nesvorný (2003) 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.

Grogan K. and Dermott S. F. (2002) The size-frequency distribution of zodiacal dust band material. In *Dust in the Solar System and Other Planetary Systems*, Proceedings of IAU Colloquium 181/COSPAR Colloquium 11 (J. A. M. McDonnell et al., eds.), submitted. Elsevier, Amsterdam.

Grogan K., Dermott S. F., and Kehoe T. J. J. (2003) The distribution of asteroidal dust in the inner solar system. In *Planetary Systems in the Universe: Observation, Formation, and Evolution*, ASP Conf. Ser. (A. J. Penny, P. Artymowicz, A. M. Lagrange, and S. S. Russell, eds.), submitted. Astron. Soc. Pacific Press, San Francisco.

Kehoe T. J. J., Dermott S. F., and Grogan K. (2002a) Evolution of asteroidal dust particles through resonance. *Memorie della Società Astronomica Italiana, 73*, 684–687.

Kehoe T. J. J., Dermott S. F., and Grogan K. (2002b) A dissipative mapping technique for integrating interplanetary dust particle orbits. In *Dust in the Solar System and Other Planetary Systems*, COSPAR Colloquia Ser. Vol. 15 (S. F. Green, I. P. Williams, J. A. M. McDonnell, and N. McBride, eds.), pp. 140–143. Pergamon, Amsterdam.

Oral Presentations

Dermott S. F. and Kehoe T. J. J. (2002) *What can our solar system tell us about other circumstellar disks?* Debris Disks and the Formation of Planets: A Symposium in Memory of Fred Gillett, Tucson.

Dermott S. F., Durda D. D., Grogan K., and Kehoe T. J. J. (2001) *Asteroidal dust* (abstract, p. 115). Asteroids 2001: From Piazzi to the Third Millenium, Palermo.

Dermott S. F., Fogle D. A., Grogan K., Holmes E. K., Vass I. M., and Kehoe T. J. J. (2000) *Dynamics of solar system particulates* (abstract 4.3, p. 18). Dust in the Solar System and Other Planetary Systems, IAU Colloquium 181/COSPAR Colloquium 11, Canterbury.

Grogan K., Dermott S. F., and Kehoe T. J. J. (2001) *Dynamics of interplanetary dust: modeling the zodiacal cloud* (abstract 01.04). 32nd Annual Meeting of the Division on Dynamical Astronomy, Houston.

Kehoe T. J. J. and Dermott S. F. (2002) *Asteroidal and Cometary Dust.* DUNE Workshop, Pasadena (`http://www.mpi-hd.mpg.de/galileo/~gruen/DUNE/program.html`).

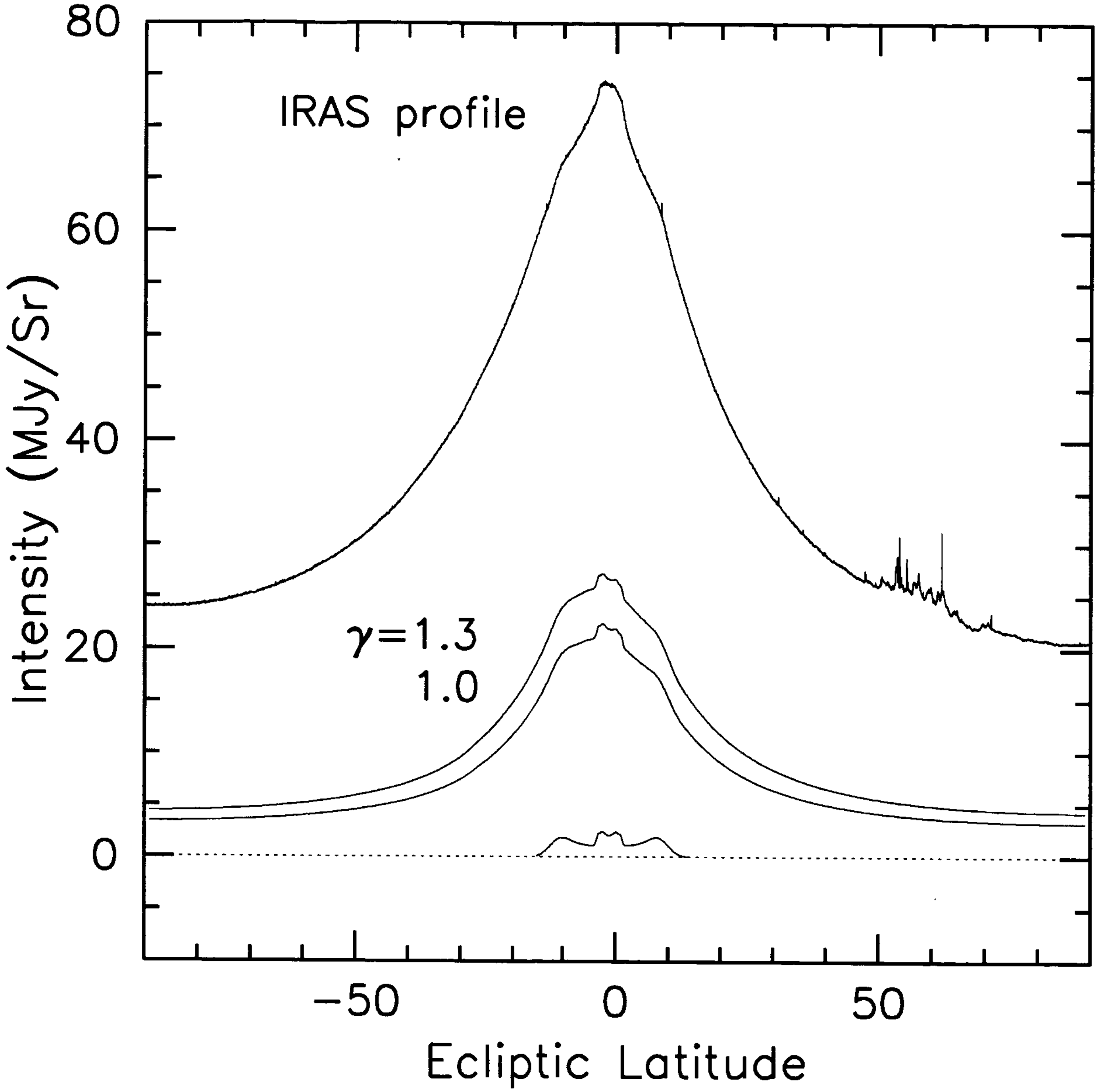

Figure 1: The $\gamma = 1.3$ and $\gamma = 1.0$ profiles in this figure were calculated assuming that the dust particles migrate from the asteroid belt to the inner solar system interior to 1 AU. The figure shows a comparison of the thermal emission obtained from two dust-band models to the corresponding unfiltered IRAS profile in the 25-μm wave band and indicates that the dust bands contribute approximately 30% to the total near-ecliptic, thermal emission. Also shown (bottom profile) is the amplitude of the dust-band material calculated assuming that the dust-band material remains confined to the asteroid belt exterior to 2 AU.

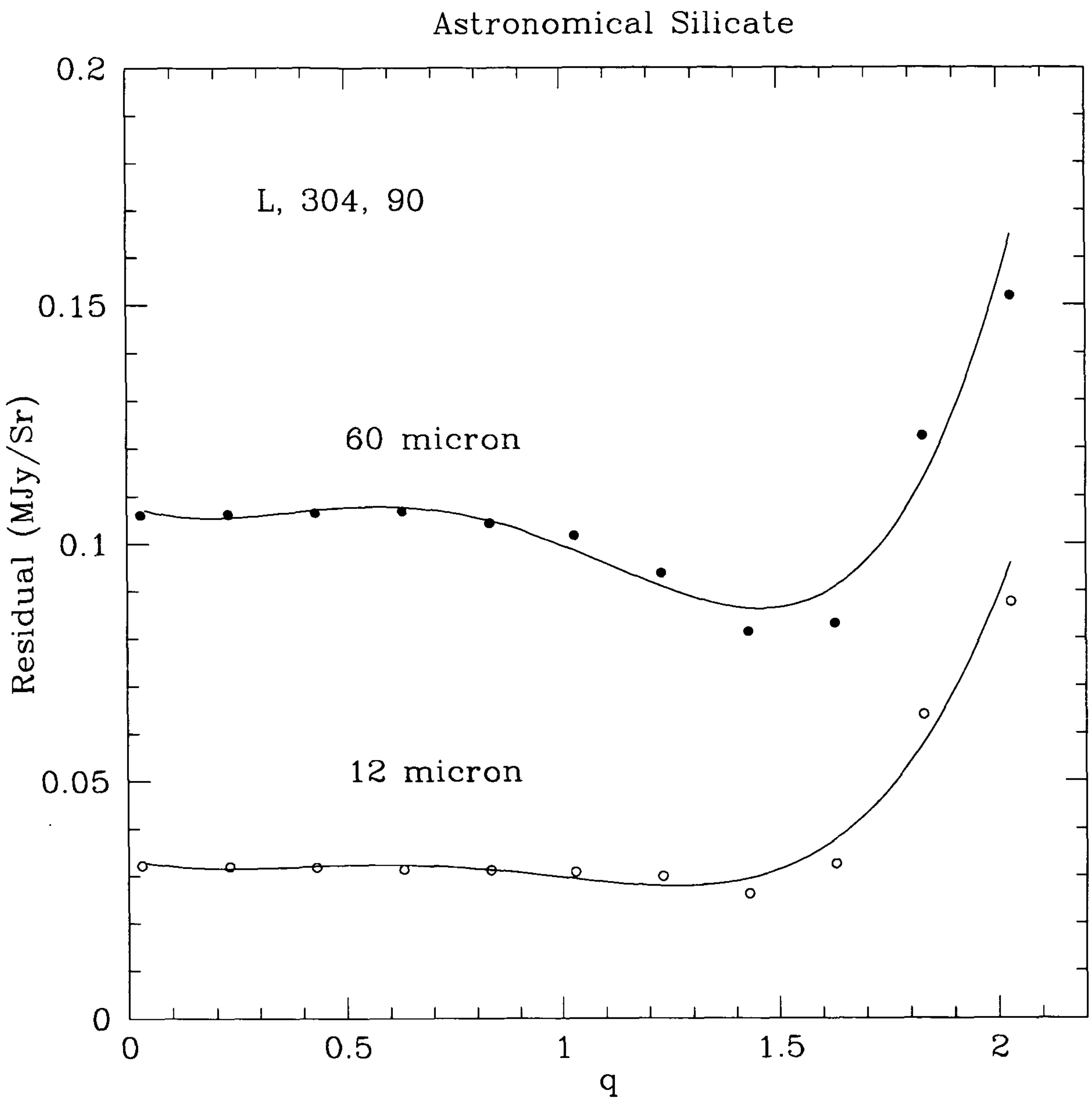

Figure 2: Evidence for large particles dominating the dust band emission: dust band model residuals as a function of size-frequency index q. These residuals are calculated for a single line of sight denoted by the legend 'L,304,90' meaning a longitude of Earth of 304° and a solar elongation of 90° in a direction leading the Earth in its orbit. They are found for the ten degree band by calculating the rms (observation-model) over two 5° wide latitude bins to cover the north and south bands for both the 12 and the 60 micron wavebands. The residuals are minimized around $q = 1.4$, although it becomes difficult to discriminate the exact value for low q since the particles in the model act like grey bodies (large diameter compared to the wavelength). The particle composition is taken to be astronomical silicate.

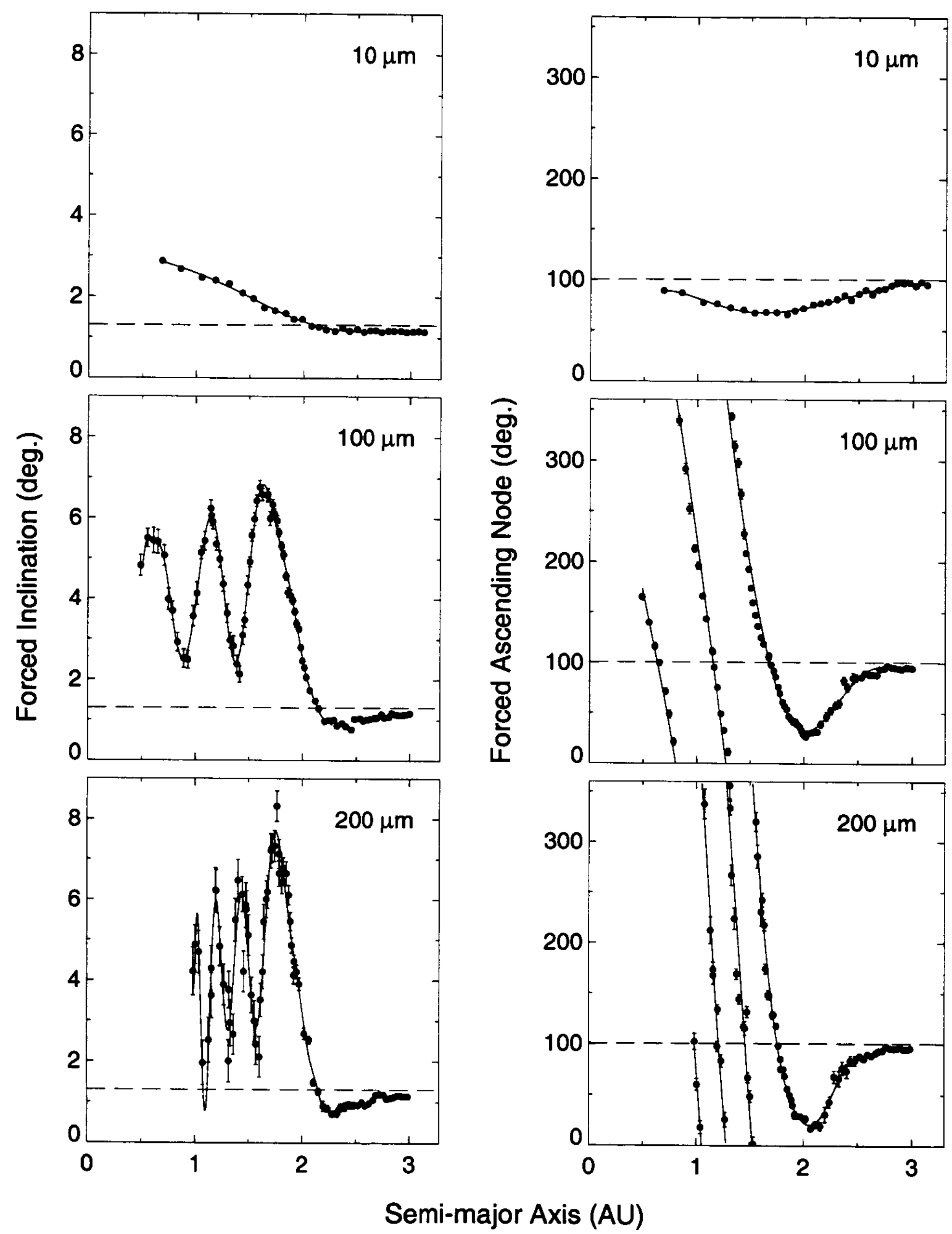

Figure 3: Variation of the forced inclinations (representative of the gravitational perturbations of the planets) and the forced longitudes of ascending node with heliocentric distance for 10, 100 and 200 micron diameter Eos family asteroidal dust particles at the present epoch. The dashed lines show the present osculating inclination and node for Jupiter, demonstrating that Jupiter dominates the orbital distribution of the particles beyond 2 AU. As the particles spiral towards the inner Solar System under the influence of Poynting-Robertson drag, a strong secular resonance near 2 AU strongly effects both the forced inclinations and nodes.

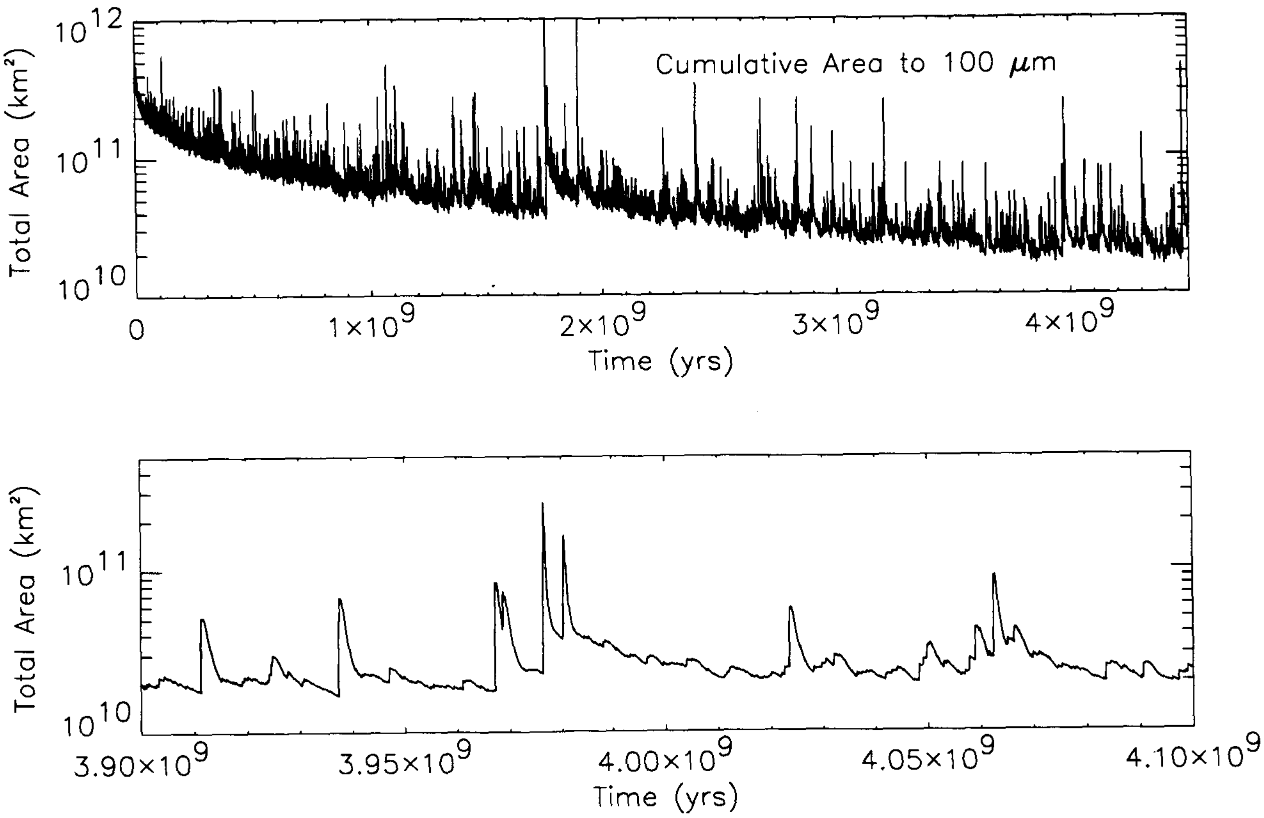

Figure 4: Variation with time of the total cross-sectional area of dust associated with the breakup of precursor asteroids that were big enough and numerous enough to supply all of the observed collision products of the main belt. This simulation modeled the stochastic breakup of asteroidal fragments, due to collisions, down to a diameter of $100\,\mu$m. A size-frequency distribution with a power-law index $q = 1.9$ was assumed for the initial breakup of each asteroid and this accounts for the height of the 'spikes' in the plots