

The History of the Solar System's Debris Disc

M. Booth¹, M.C. Wyatt¹, A. Morbidelli², H. F. Levison³ and A. Moro-Martín⁴

¹Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA, UK

²Observatoire de la Côte d'Azur, Nice, France

³Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, USA

⁴Department of Astrophysical Sciences, Peyton Hall, Ivy Lane, Princeton University, Princeton, NJ 08544

E-mail: mbooth@ast.cam.ac.uk



Abstract

One of the main ways of understanding extrasolar planetary systems is to use what we know about our own Solar System. The Nice Model of Gomes et al. (2005) suggests that during our Solar System's history, the giant planets migrated from their original locations which destabilised the orbits of many Kuiper Belt Objects, causing them to be thrown inwards and leading to the Late Heavy Bombardment (LHB). Here we investigate the IR emission from the Kuiper Belt during the history of the Solar System as described by the Nice Model. We compare our results with observed debris discs and evaluate the plausibility of detecting an LHB-like process in extrasolar systems.

1. Introduction

Over the past couple of decades, many stars have been found to be orbited by debris discs. Most of these can be explained by large, quasi-static, Kuiper Belt analogues (Moro-Martín et al. 2007). However, it has been shown that some of these belts possess abnormally large quantities of hot dust at ~1AU and cannot be explained by a quasi-static belt and must be transitory in nature (Wyatt et al. 2007). Current theories about the history of the Solar System suggest that such a transitory event did occur. Evidence from cratering rates of the Moon show a spike in the impact rate at approximately 3.9Ga (billion years ago) which has since become known as the late heavy bombardment (Tera et al. 1974).

There are many theories which attempt to explain the LHB (e.g. Levison et al. 2001; Chambers 2007). The theory which we will be basing our model on is the Nice Model, which says that the instability was caused by the migration of the giant planets (Gomes et al. 2005). The Nice model was designed to explain the current orbital elements of the outermost planets (Tsiganis et al. 2005). It shows that the gas giants formed much closer together with Uranus originally being the outermost planet. Due to interactions with the planetesimal disc, Saturn, Neptune and Uranus migrated outwards and Jupiter migrated slightly inwards. When Jupiter and Saturn crossed their 2:1 mean motion resonance the system became temporarily destabilised, affecting the orbital elements of the gas giants. This destabilisation also caused a large number of Kuiper belt objects to be thrown into the inner Solar System and disrupted the asteroid belt due to the effects of secular resonances (Gomes 1997).

2. Modelling

Our model is based on KBO and planet data (for the 4 giant planets only) from the Nice model (Gomes et al. 2005). In the Nice model, the simulation begins with 500 particles, each representing $2.1 \times 10^{-7} M_{\odot}$ of Kuiper belt objects. These particles are separated into 20 equal mass particles when they 'become interesting' (i.e. approach Neptune). At the time of the Jupiter-Saturn resonance crossing all of the particles are cloned. Any particles that evolved onto orbits that either leave the Solar System or have a perihelion less than 1AU were removed from the simulation. The simulation runs for 1.2Gyr starting at the time at which the gas disc dissipates. Figure 1 shows the orbits of the planets and positions of the particles at 3 times during the simulation.

When this data is input into our model, all of the original particles are cloned 20 times with each clone given the same orbit as the original particle but a randomised mean anomaly. This makes sure that all of the particles are the same mass. This data can then be used to determine the mass distribution in the system. Using the mass distribution and assuming a collisional cascade with q_d (the size distribution constant) between 5/3 and 2, we can then find the cross-sectional area distribution (Wyatt et al. 2007):

$$\sigma_{\text{tot}} = \frac{M_{\text{tot}}}{2.5 \times 10^{-9} \rho D_{\text{bl}}} \left(\frac{6 - 3q_d}{3q_d - 5} \right) \left(\frac{D_{\text{bl}}}{10^9 D_c} \right)^{6-3q_d}$$

where M_{tot} is the total mass in Earth masses, ρ is the particle density, D_c is the diameter of the largest particle and D_{bl} is the size below which particles are blown out by radiation pressure. By also calculating the black-body emission from the particles we can find the flux density measured by a distant observer:

$$F_{\nu} = 2.35 \times 10^{-11} \sigma_{\text{tot}} B_{\nu}(\lambda, T) d^{-2}$$

$$T = 278.3 L_*^{1/4} r^{-1/2}$$

where B_{ν} is the Planck function, which is dependent on the wavelength(λ) and temperature(T), d is the distance to the observer (arbitrarily chosen to be 10pc), L_* is the luminosity of the star and r is the distance between the dust and the star.

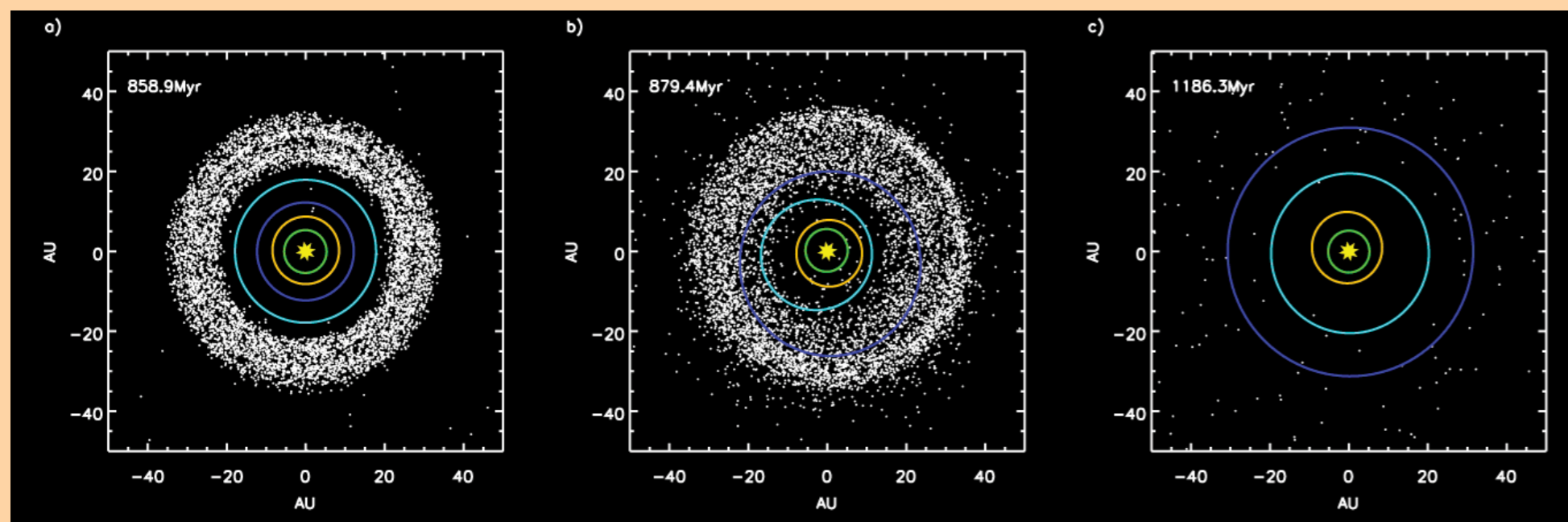
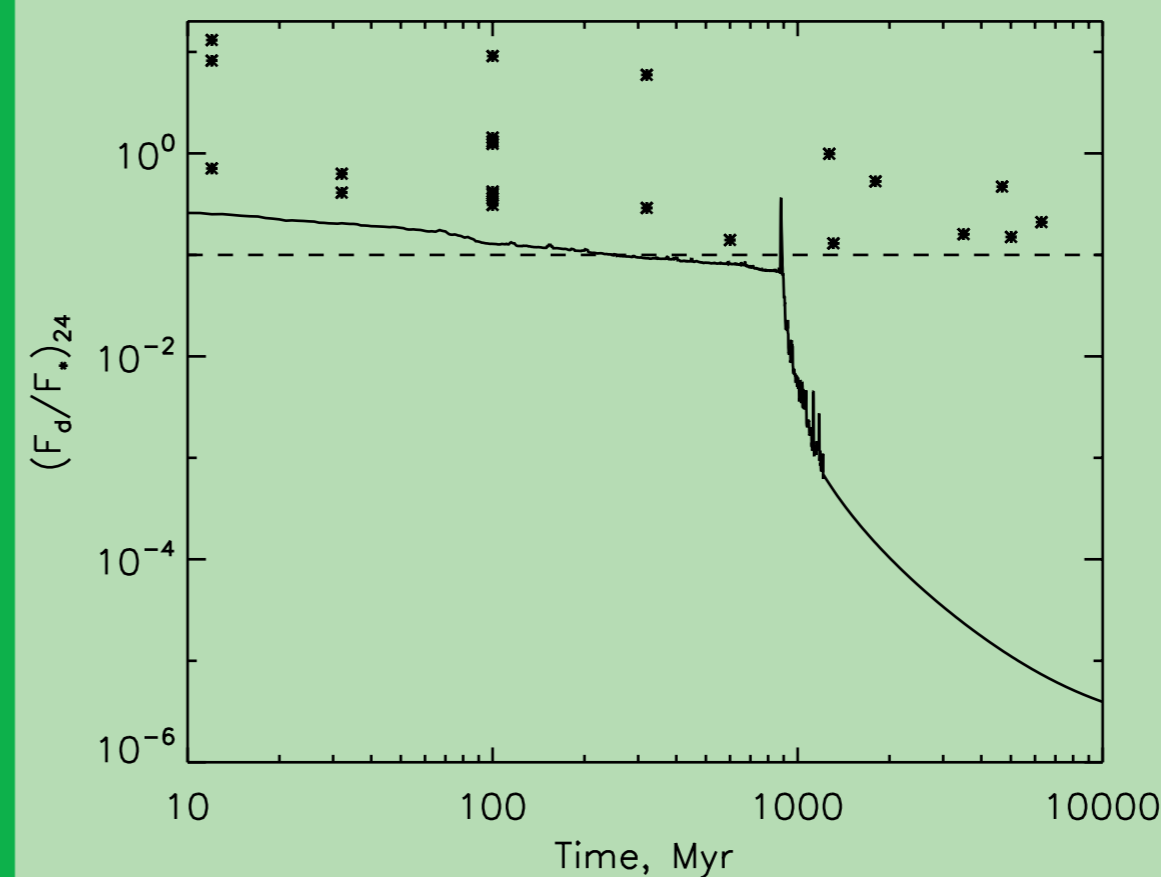
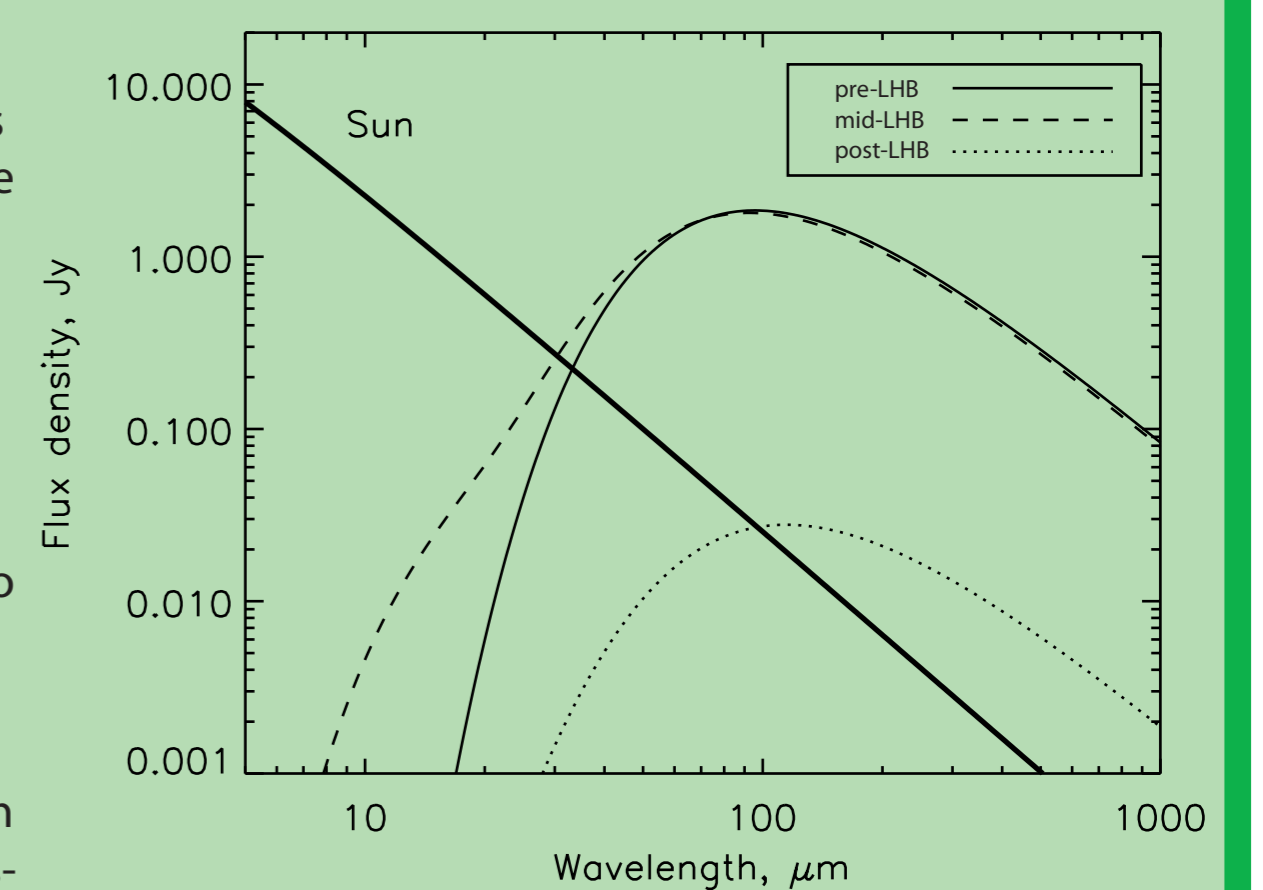


Figure 1. Plots showing outer planets and Kuiper Belt: a) Before Jupiter/Saturn 2:1 resonance b) Scattering of Kuiper Belt objects into the solar system after the orbital shift of Neptune c) After ejection of Kuiper Belt bodies by Jupiter

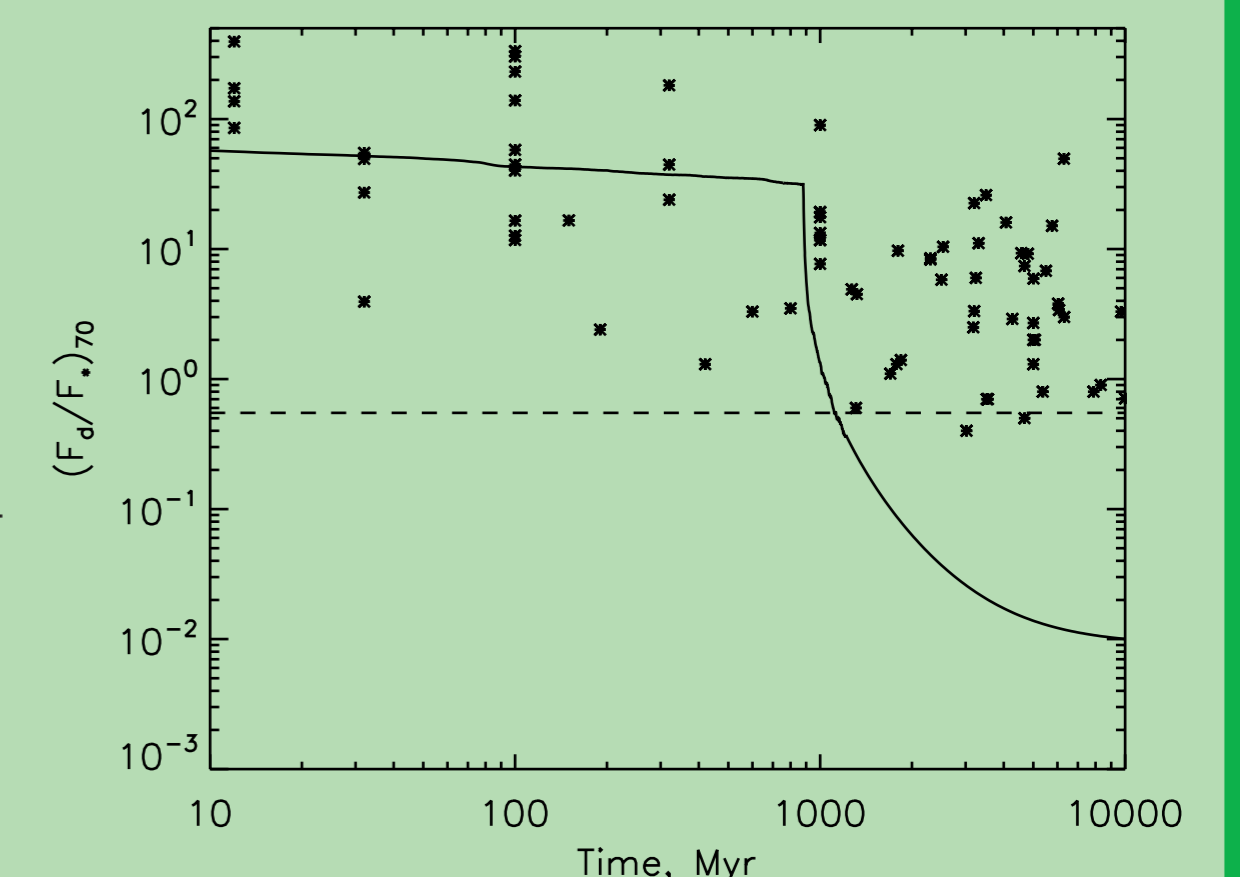
3. Results and Discussion

By plotting the flux density against wavelength for the dust emission (right) we can see that the MIR flux is greatly increased during the LHB. The flux then rapidly decreases after the LHB has occurred. The increase in MIR flux seen here is only a lower limit, since objects with perihelion less than 1AU are removed from the simulation, which removes a lot of planetesimals that are scattered onto cometary orbits. These would otherwise contribute to the emission via dust production and sublimation. This model also lacks asteroids which would help to enhance the MIR emission.



The fractional excess at 24 μm and 70 μm are shown left and below respectively. These plots also show the limit of detectability (dashed line) and observed debris discs (asterisks). From the 24 μm excess, we can see that the hot emission drops below the limit of detectability after about 200Myr and then briefly rises again during the LHB. This would have made it detectable during the LHB, showing that some of the observed systems may be going through a similar process, although the spike in emission only lasts for 15Myr.

The 70 μm excess remains in a quasi-steady state until the LHB at which point it drops off sharply. The cold emission drops below the limit of detectability after about 1Gyr. The plot shows that there are a large number of observed discs at late times, meaning that a major, planetesimal-clearing event, like a late heavy bombardment, is not necessarily a common event and would not have occurred in these systems. We can also see from this simulation that the Sun would have been amongst only 16% of stars that have detectable 70 μm excess after the protoplanetary disc phase.



4. Future Work

In this work we have only concentrated on the emission from the Kuiper Belt. Since this is far from the Sun most of the emission will be from cold dust and thus we are underestimating the warm emission and, therefore, the 24 μm flux. In future work we intend to add comets and asteroids to this model.

We have also made some assumptions about the particles, the most notable being that we are dealing with black-body grains and that the Kuiper Belt has a single slope size distribution. In future work we intend to investigate more realistic grain properties. We also intend to incorporate a three slope size distribution and investigate the evolution of this size distribution.

References

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