A&A 499, L13–L16 (2009)
DOI: 10.1051/0004-6361/200811609

Astronomy & Astrophysics

Letter to the Editor

Dynamical stability of the inner belt around Epsilon Eridani

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Received 31 December 2008 / Accepted 17 April 2009

ABSTRACT

Context. Recent observations with Spitzer and the Caltech Submillimeter Observatory have discovered the presence of a dust belt at about 3 AU, internal to the orbit of known exoplanet ϵ Eri b.

Aims. We investigate via numerical simulations the dynamical stability of a putative belt of minor bodies, as the collisional source of the observed dust ring. This belt must be located inside the orbit of the planet, since any external source would be ineffective in resupplying the inner dust band.

Methods. We explore the long-term behaviour of the minor bodies of the belt and how their lifetime depends on the orbital parameters of the planet, in particular for reaching a steady state.

Results. Our computations show that for an eccentricity of ϵ Eri b equal or higher than 0.15, the source belt is severely depleted of its original mass and substantially reduced in width. A "dynamical" limit of $\simeq$0.10 comes out, which is inconsistent with the first estimate of the planet eccentricity (0.70 ± 0.04), while the alternate value (0.23 ± 0.2) can be consistent within the uncertainties.

Key words. stars: planetary systems – minor planets – asteroids – celestial mechanics – stars: individual: Epsilon Eridani

1. Introduction

The nearby star ϵ Eridani might have a miniature solar system around it. A long-period Jupiter class planet orbiting at about 3.4 AU, named planet "b", was discovered by Hatzes et al. (2000) from radial velocity measurements. Graves et al. (1998) and Graves (2005) took submillimeter images of the star environment and found evidence of a nearly circular dusty ring extending from 30 to 110 AU from the star. This debris disk might be material left over from the early stages of planetary formation. The properties of the disk suggest the possibility of a planet "d" at about 40 AU from the star. Moreover, an infrared excess within 4.5" of the star may indicate an additional internal structure.

A recent analysis, made on Spitzer observations of ϵ Eridani by Backman et al. (2009), suggests a more complex spatial structure of the dusty disk. The infrared excess has been interpreted as the result of two additional warm dusty rings: a narrow belt of small (about 3 μm) silicate grains located at about 3 AU and a second belt at 20 AU. We concentrate on the innermost belt by exploring the possibility that it can be caused by fragmentation and cratering events involving a population of bodies large enough not to be affected by P-R drag. These bodies must be stable against the perturbations of planet "b"; otherwise, the whole belt would have been wiped away by now. The star is in fact from 500 Myr to 1 Gyr old. Additional sources external to the planet orbit cannot in fact supply material, drifting inwards by non-gravitational forces (P-R drag), to the inner belt due to the barrier raised by the planet strong gravity.

A pioneering work by Moran et al. (2004) described the evolution of the dusty belt under the dynamical perturbations of the inner planet and P-R drag, showing that the primary features of the resulting central dust distribution are clumps of particles trapped in mean motion resonances. However, Figs. 2 and 4 of their paper show that the particle density dramatically drops within the orbit of planet "b".

As a further test, we numerically integrated the trajectories of a large number of 3 μm dust grains (the size obtained from the model in Backman et al.) started outside the orbit of the planet. We consider 4 different rings (centred at 5, 6, 7, 8 AU) and let the particle evolve for 7×10^5 yr under P-R drag and planetary perturbations. We find that less than 5% of the dust grains can pass the planet orbit and reach the inner region (Fig. 1). In addition, their lifetime once inside the planet is very short either because they are ejected out of the system after a close encounter with the planet or because their drift rate is very high due to their large eccentricity. The dust grains travelling within the planet orbit have on average an eccentricity greater than 0.5 and reach the star on a timescale of about 10^4 yr driven by P-R drag. The peaks in Fig. 1, giving the fraction of particles inside the planet orbit, decay in fact very rapidly for any outer source considered.

The total mass in the innermost belt, estimated by Backman et al. (2009) from infrared fluxes, is about 10^{21} g. Invoking an external source would require at least 2×10^{26} g (about 0.03 Earth masses) of material flowing past 5 AU in the past 100 Myr. This estimate accounts for the short lifetime of dust inside the planet orbit (shorter than 10^4 yr) and for the lack of efficiency of the transport mechanism. It seems unlikely that such a huge flux of mass can be produced by the collisional evolution of an external belt, also accounting for the reduction of the transport efficiency getting farther away from the planet (see Fig. 1). If the inner belt is not the result of a very recent event (within the past 10^4 yr), the most reliable way to explain its existence is to invoke the possibility of a local belt of large bodies producing dust by

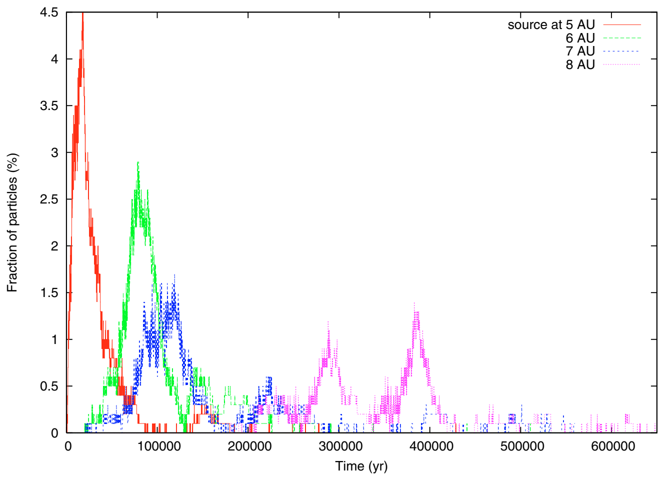

Fig. 1. Evolution with time of the fraction of dust particles residing inside the planet orbit for different possible outer sources.

mutual collisions. They might be planetesimals left over from the planet formation process.

The most critical parameter for the stability of the parent belt is the eccentricity e_p of planet "b". Beyond a certain value of e_p, a large chaotic region appears within the planet orbit, triggered by mean-motion resonance overlap. No kind of disk debris can survive long enough in this region to explain the observed ring of dust.

Previous estimates of the planetary eccentricity, based on radial velocity and astrometric measurements, gave $e_p = 0.70 \pm 0.04$ (Benedict et al. 2006). This value clearly contradicts the existence of the inner belt, as already suggested by Backman et al. (2009); a different estimate reduces e_p to 0.23 ± 0.20 (Butler et al. 2006).

We use the symplectic code SyMBA (Levison & Duncan 2000) to explore the stability of the parent belt for different values of e_p. We concentrate on dust precursors and in our simulations neglect any non-gravitational force. We first analyse the source of instability for bodies populating the belt and then compute its evolution towards the steady state by integrating over 20 Myr.

Section 2 describes the numerical model and the simulation set up, while Sect. 3 shows the results. Section 4 is devoted to some final considerations.

2. Numerical set up

According to Backman et al. the innermost dusty belt in ϵ Eridani is centred at about 3.00 ± 0.75 AU with a width of 1.00 ± 0.25 AU. Our model starts with a belt of massless bodies orbiting between 1.9 and 2.9 AU. This belt is moved slightly inside with respect to the model proposed by Backman et al., but it accounts for the strong instability caused by planet "b" when we approach its orbit.

The bodies were initially placed in the orbital plane of the planet assuming circular planar orbits. The planet ϵ Eri b is set at 3.39 AU, with zero initial longitude of pericentre, and its eccentricity has been kept fixed during the simulation: this is probably an approximation, because the suspected presence of – at least – a second planet would cause a secular oscillation of the eccentricity and the circulation of the pericentre argument.

We used two different sets of test particles:

- the first set consists in 100 bodies equally spaced between 1.9 and 2.9 AU, with pericentres initially aligned with the planetary one. It has been used to grasp the basic dynamical features of the belt caused by the gravitational pull of the planet. We varied the eccentricity of the planet e_p from 0 to 0.45 at equal steps of 0.05. The outcomes of these simulations were also used to approximately detect a tentative limiting value of e_p compatible with the inner belt;
- the second set consists in 1000 equally spaced bodies, but with initial pericentre arguments chosen randomly. In this case we recorded the number of bodies (and their orbital elements) surviving within the belt every 5×10^5 yr. For the most interesting range of planet eccentricity values (e_p = 0.05, 0.10, and 0.15), we extended the numerical integrations for 2×10^7 yr when a steady state was reached.

To speed up the computation, those bodies undergoing close encounters with the planet (inside its Hill's sphere) have been considered lost and discarded from the model. Particles with semimajor axes $a > 100$ AU or $a < 0.01$ were also discarded. We chose 10 days – about 1/100 of the shortest period in the system – as the symplectic timestep.

3. Belt evolution and stability

3.1. Dynamical behaviour

From the outcome of the short-term integrations, we divided the dynamical behaviour of the bodies into three classes:

- *Stable*: the semimajor axis and eccentricity oscillate regularly in time with constant amplitude (Fig. 2, left panel);
- *Quickly unstable*: their orbital elements vary rapidly with time, leading to ejection from the belt on a relatively short timescale (Fig. 2 middle panel);
- *Mildly unstable*: the bodies jump chaotically between different resonant states because of resonance overlap, but remain in the belt for an extended period of time. As the planetary eccentricity increases, this behaviour is more frequently only transient, followed by a final ejection of the particle, as shown in Fig. 3. A reliable identification of the regions strongly influenced by resonances requires a longer integration time and a more systematic exploration of the initial conditions. We discuss this point in the next section.

By changing the eccentricity of the planet we have different fractions of bodies in the belt following the above-mentioned behaviours. For instance, for $e_p = 0$ the most stable situation is met. Almost all bodies are stable with a narrow instability strip between 2.85 and 2.90 AU (4:3 and 5:4 resonances). As the planetary eccentricity increases, the belt becomes more unstable, more particles escape within 100 kyr, and the zones where we have chaotic motion are wider. For $e_p > 0.15$, the whole belt becomes chaotic, with the exception of a region between 1.9 and 2.2 AU.

3.2. Reaching a steady state

The number of bodies in the belt surviving as long as 20 Myr is shown in Fig. 4, for three values of e_p (0.05, 0.10, and 0.15). In all cases we have a rapid initial depletion until a steady state is reached. On average, the population stabilises after 10^6 yr or less, with a decrease of a few units in the past ten million years;

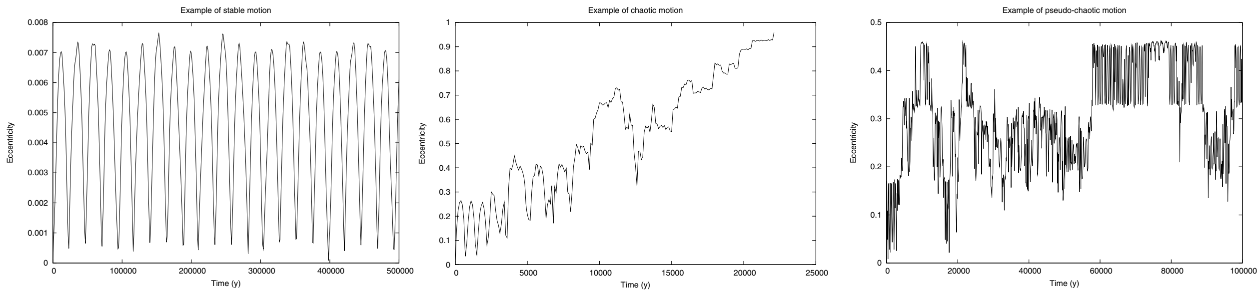

Fig. 2. Different behaviours of a test particle in the range 1.9–2.9 AU, during a short-time dynamical evolution (100 kyr). Further explanations in the text.

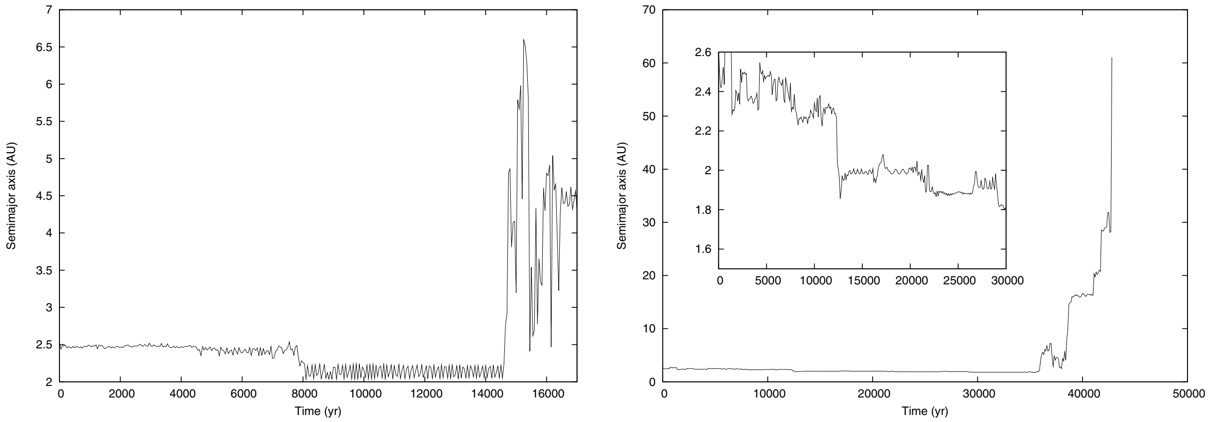

Fig. 3. Examples of particles jumping between overlapped resonances in the inner belt before escaping. Planetary eccentricity is $e_{\rm p} = 0.10$ (*left panel*) and $e_{\rm p} = 0.15$ (*right panel*).

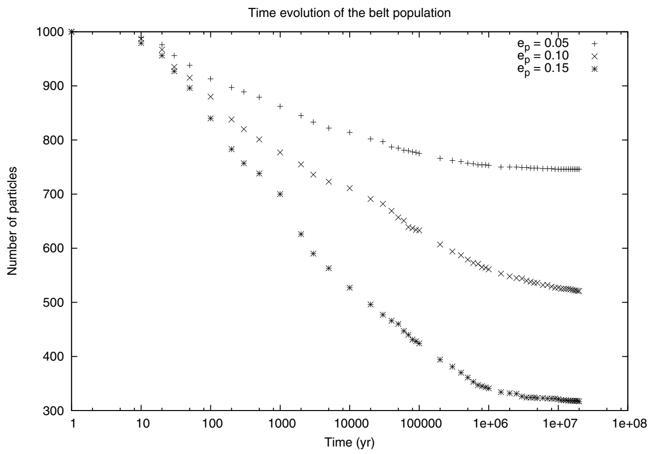

Fig. 4. Time evolution of the belt population for three different values of $e_{\rm p}$.

therefore, our relatively short timespan seems to be sufficient to predict the long-term survival of the belt.

These results are obtained within a 3-body model. As previously stated, the possibility of a second planet would further decrease the belt stability perturbing the orbit of planet "b". In this case the timescale for the belt evolution might be different and possibly related to the secular evolution of the planetary system.

The observed initial fast depletion, on timescales of 10^4 yr, mostly stems from strong instability quickly leading to a close encounter with the planet. Moreover, for $e_{\rm p} \sim 0.37$ the Hill's sphere of the planet reaches a minimum radius of

$$r_{\rm min} = (1 - e_{\rm p})a_{\rm p} - r_{\rm H}$$

corresponding to the inner boundary of the belt, depleting it completely in a very short time. In a simulation performed with $e_{\rm p} = 0.37$, only one body survives after 1000 years. This defines a kind of geometrical limit on $e_{\rm p}$ for the mere existence of the belt, which also applies to the (more complex) evolution of the – observed – dust belt.

In Fig. 5 we plot the orbital element distribution of the bodies surviving at the end of the simulations in the (a, e) plane. Dashed vertical lines mark the most relevant mean motion resonances. We also plot the histogram of the number of bodies corresponding to various semimajor axis bins. For $e_{\rm p} = 0.05$ and 0.10, some excess survivors are clustered around the 3:2 and 4:3 resonances. At the 7:5 resonance location, an unstable region is clearly visible in the plot with $e_{\rm p} = 0.10$. The behaviour of the other major resonances is unclear, even if a marked increase in eccentricity around the 2:1 can be observed.

For $e_{\rm p} = 0.15$, resonances produce large gaps not only at their locations but also in between, a clear indication of resonance overlap. Almost the whole belt is depleted beyond 2.25 AU, and the inner residual belt cannot replenish the outer regions since non-gravitational forces only move particles inwards. A few bodies appear to be permanently trapped at the 3:2 resonance, however their total mass is less than 2% of the original mass. According to Chen & Jura (2001), the amount of mass in source bodies needed to produce the observed dust ring exceeds that of the present asteroid belt in our Solar System. As a consequence, the bodies trapped at the 3:2 resonance could be the source of the observed dust ring only if they were part of an original belt almost 2 orders more massive than our asteroid belt. This is an unlikely scenario.

In conclusion, the dust properties obtained from the spectral energy distribution seem to be consistent with a planet

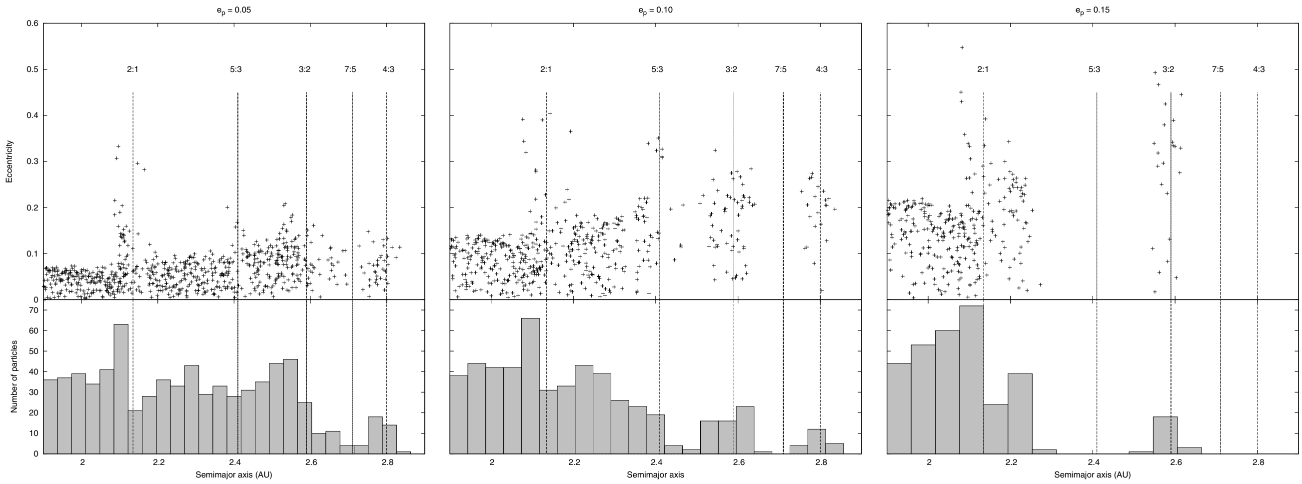

Fig. 5. Eccentricities and semimajor axes of the belt particles after 20 Myr of dynamical integration. The vertical lines indicate the position of the most relevant resonances. In the lower plots, we represent the corresponding histograms.

eccentricity not greater than about $e_\mathrm{p} = 0.10$. For larger eccentricities the source planetesimal belt would be too depleted.

4. Discussion of results

An inner debris belt in the ϵ Eri system imposes an upper limit on the eccentricity of planet "b". Its value has to be in the range 0.1–0.15.

As previously discussed, we have two different estimates of e_p obtained from radial velocities and astrometric measurements: the former (Benedict et al. 2006) is clearly inconsistent with our limit; the latter (Butler et al. 2006) seems to be rather high, but consistent with our results within the error bars.

We note that our conclusions could be falsified essentially in two ways, both of them rather unlikely:

- The source of the dust is extremely massive (in this case it could come also from the region external to planet "b");
- The dust has been created by a recent event.

We must finally recall that the existence of a second planet could produce a perturbation on the orbit of ϵ Eri b, thus leading to further destabilisation.

Acknowledgements. We are grateful to the referee M. Kuchner for useful suggestions. The work has been supported by ASI funds.

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