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On the formation and evolution of asteroid belts and their potential significance for life

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ABSTRACT

Suggestions have been made that asteroid belts may be important both for the existence of life and perhaps even for the evolution of complex life on a planet. Using numerical models for protoplanetary discs, we calculate the location of the snow line, and we propose that asteroid belts are most likely to form in its vicinity. We then show that observations of warm dust in exosolar systems, thought to be produced by collisions between asteroids in a belt, indicate that asteroid belts (when they exist) indeed coincide with the radial location and the temperature of the snow line. Giant planets form outside the snow line and prevent planet formation just inside of their orbit, creating an asteroid belt there. However, the migration of giant planets through the asteroid belt likely disperses the compact formation. We examine existing observations of giant exoplanets and find that less than 4 per cent are at radial locations outside of the snow line. This definitely may be the consequence of observational selection effects. However, with this caveat in mind, we point out that the dearth of giant planets outside the snow line may also suggest that compact asteroid belts are not common, and more speculatively that complex life may not be expected in most of the currently observed systems.

Key words: minor planets, asteroids: general – planets and satellites: formation – protoplanetary discs.

1 INTRODUCTION

Asteroid belts can (in principle at least) affect the habitability of a planet, the emergence of life and potentially even the evolution of complex life in several important ways. Terrestrial planets typically form in a dry region of a protoplanetary disc (Martin & Livio 2012). Water therefore must be later delivered to the planet's surface, most likely by asteroids (e.g. Morbidelli et al. 2000), although other sources, such as comets and the interaction between the magma and atmosphere, have been suggested (Lunine 2006; Genda & Ikoma 2008). The formation of large moons may also require an asteroid collision (Canup & Asphaug 2001), although, here again, a different origin for the impactor has been considered (e.g. Belbruno & Gott 2005). Our Moon, for instance, stabilizes the rotation axis of the Earth and prevents weather extremes that would have resulted from chaotic motion. This process may not be universal, since it depends on initial conditions. According to some hypotheses, life itself may have been delivered to Earth by an asteroid (e.g. Cronin 1983; Castillo et al. 2008; Houtkooper 2011). Heavy elements, including some that are essential for life, were also probably delivered to the Earth's crust through collisions (Willbold, Elliott & Moorbath 2011). During the early times of formation, the Earth was molten and its gravity pulled heavy elements to its core, leaving the crust depleted of elements such as iron, gold and platinum. On a much more speculative note, the asteroid impact that led to the extinction of the dinosaurs on Earth (Alvarez et al. 1980) may have allowed for the emergence of dominant mammals and intelligent life. The point is that even if only one of these ideas turns out to be true, it makes it extremely intriguing to examine the formation and evolution of asteroid belts and consider the possibility for complex life in other observed solar systems.

The asteroid belt in our Solar system is located between the inner terrestrial planets and the outer giant planets, between Mars and Jupiter. It contains millions of irregularly shaped bodies made of rock, ices and metals with a total mass of about 4 per cent of that of the Earth's moon. Studying the asteroid belt allows us a glimpse into the early stages of planet formation. Observations suggest that at the time of planetesimal formation the location of the snow line was within the asteroid belt. The snow line marks the radius outside of which ice forms. The inner asteroids, closest to Earth, are water devoid, while outside a radius of about 2.7 au the asteroids are icy C-class objects (e.g. Abe et al. 2000; Morbidelli et al. 2000).

The asteroid belt formed from planetesimals within the solar nebula. In the generally accepted scenario, planetesimals stuck together to form larger and larger bodies until the protoplanets were formed. It is thought that the asteroid belt exists because gravitational perturbations from Jupiter gave the planetesimals inside of its orbit too much orbital energy to form a planet. The violent

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collisions produced fragmentation rather than fusion (e.g. Edgar & Artymowicz 2004). The picture that we envisage and examine in the current work, which was first observationally motivated by Morales et al. (2011), is the following: giant planets likely form by core accretion outside of the snow line where the solid mass density is much higher because of water ice condensation (Pollack et al. 1996). Consequently, we propose that if an asteroid belt forms at all, *its location is likely to be around that of the snow line*. Simulations of the formation of terrestrial planets agree with this scenario (e.g. Raymond et al. 2009). The habitable, rocky terrestrial planets should form inside the snow line, as was the case in our own Solar system.

Observational evidence suggests that Jupiter formed close to its current location. The generally accepted theory of the formation of our Solar system infers that Jupiter migrated through planetesimal interactions only by about 0.2–0.3 au (e.g. Morbidelli et al. 2010). The asteroid belt is thought to have originally contained about an Earth mass. As Jupiter migrated slightly inwards, its gravitational perturbations caused the majority of the mass to be ejected, leaving behind only about 0.1 per cent of the original. Jupiter is still responsible for nudging asteroids and sending them towards the inner Solar system. It is unlikely that complex life would have been able to develop on Earth had the asteroid belt remained as massive as it had originally been, because there would have been far too many devastating impacts. However, it is probably also unlikely that complex life on Earth would exist had all of the asteroids been scattered away.

To test our suggestion for the location of asteroid belts, in Section 2, we first use detailed protoplanetary disc models to examine the location of the snow line for different stellar masses. We then describe and tabulate the observations of warm dust that may indicate the presence of exoasteroid belts and show that their locations coincide with the snow line. The formation of the asteroid belt depends on the formation of an exterior giant planet. In Section 3, we therefore consider observations of giant planets in exosolar systems and discuss the implications of their locations for the presence of terrestrial planets in the habitable zone and the likelihood of a compact asteroid belt. We also examine the question of how special our Solar system is.

2 ASTEROID BELTS AND THE SNOW LINE

In this section, we calculate numerical models of protoplanetary discs to determine the snow line evolution. We then examine observations of warm dust that may indicate the presence of exoasteroid belts and show that their radial locations coincide with the theoretical radius of the snow line.

2.1 Theoretical models of the snow line

The snow line marks the distance from the star outside of which ice forms. It is thought to occur at temperatures of around 170 K (e.g. Lecar et al. 2006). Marseille & Cazaux (2011) find that there is an extended region down to almost 100 K, the snow border, in which both icy and dry planetesimals can coexist. Particles migrating through the disc accumulate near the snow line over a short radial extent and grow through collision (Kretke & Lin 2007). Planetesimal formation rates increase by an order of magnitude or more moving across the snow line when the solid surface density increases by a factor of 2 (Chambers 2010).

To model the evolution of the snow line, we used a detailed model for a layered protoplanetary disc of the type first described in Armitage, Livio & Pringle (2001) and further developed in Zhu, Hartmann & Gammie (2010) and Martin & Lubow (2011). We should note that our model is different from previous models that assumed a fully turbulent disc (e.g. Oka, Nakamoto & Ida 2011) and failed to explain the current location of the snow line in the Solar system (see Martin & Livio 2012, for a discussion). In our model, the magnetorotational instability (MRI) drives turbulence and angular momentum transport within the disc if it is sufficiently ionized (Balbus & Hawley 1991). However, protoplanetary discs are thought to contain dead zones at the mid-plane (a region of zero MRI turbulence), because they are too cool for thermal ionization, and cosmic rays or X-rays do not penetrate the entire disc (Gammie 1996). We used a critical magnetic Reynolds number, $Re_{\rm M,\,crit} = 5 \times 10^4$, to determine the precise extent of the dead zone (e.g. as in Martin et al. 2012a,b). In our simulations, where a dead zone is present, material accumulates and flows only through the active layers on the surfaces. Once sufficient material collects, the dead zone becomes self-gravitating and a second type of gravitational turbulence is driven. The increased heating leads to the MRI being triggered in the dead zone and FU Orionis type outbursts. In the present work, we are interested in the detailed structure of the disc at late evolutionary times, after the outbursts have ceased.

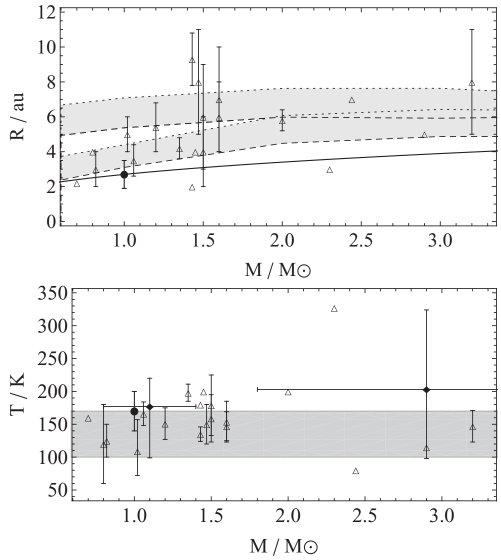

Figure 1 Upper panel: radius of the observed warm dust. The shaded regions show the snow border found from numerical models at times $t = 10^6$ yr (upper) and $t = 10^7$ yr (lower). The solid line shows the analytic approximation to the snow line given in equation (1). Lower panel: temperature of the observed warm dust. The shaded region shows the snow border. In both plots, the open triangles show the individual systems shown in Table 1. The filled diamonds (only in the temperature plot) show two samples from Morales et al. (2011) and the error bars show the range in the samples. The filled circles show the location of our Solar system's snow line and the range shows the extent of our asteroid belt.

We found that the snow line of the disc moves in over time (as was also shown in Martin & Livio 2012). Here, we use the same disc model as in Martin & Livio (2012) but we expand the calculation and consider central stars of different mass, M. For each stellar mass, we numerically evolve the time-dependent disc model up to a time of 10^7 yr, and in Fig. 1 we show the radius, R, of the inner and outer edges of the snow border that correspond to temperatures of $T = 170$ and 100 K at times $t = 10^6$ and 10^7 yr. We find that the location of the snow line is only weakly dependent on the mass of the star. We can heuristically understand the general shape of the snow line location as a function of stellar mass by the following simple argument. Since the generated power is due to accretion, $T^4 \propto M/R^3$. Scaling to the radial location of the snow line in our Solar system, we have

$$R_{\rm snow} \approx 2.7 \left(\frac{M}{\rm M_\odot}\right)^{1/3} \text{au}. \quad (1)$$

Fig. 1 shows that this analytic expression for the shape of the snow line is a reasonable approximation for the minimum snow line radius for the numerical models considered in this work.

2.2 Observations of exoasteroid belts

Dusty discs thought to be analogous to the asteroid belt in our Solar system have been inferred around main-sequence stars from their thermal infrared emission. Surveys from space-based mid- and far-infrared observations suggest that around 10–30 per cent of main-sequence stars have an infrared excess (Lagrange, Backman & Artymowicz 2000). Most of these show colour temperatures of those expected for cold dust in our Kuiper belt (Meyer et al. 2007). However, a small fraction also show inner warm dust that may indicate the presence of a (more massive) asteroid belt like structure. We note that, because we only see the dust and not the larger asteroids, there may be other explanations for its presence. For instance, the dust may be the result of planet formation (Kenyon & Bromley 2004) or of stochastic events such as the period of late heavy bombardment in our Solar system (Wyatt et al. 2007). Consequently, it is not known how common asteroid belts truly are (Chen et al. 2009). For example, our own asteroid belt is below the current limit of observability in exosolar systems.

In Table 1, we show all the debris discs we have found in the literature that have a warm component, which could be interpreted as an asteroid belt, with a measured temperature and inferred radius. We also include the median temperature values for two samples from Morales et al. (2011) for which radii have not been determined. We do not include dust with very high temperatures ($\gtrsim$400 K) as this is more likely to represent a planetary collision (e.g. Rhee, Song & Zuckerman 2008). Fig. 1 shows that the observed warm dust belts have temperatures similar to the temperature of the snow line, suggesting that they coincide with the snow line. The inferred radii also agree well with our numerical models of the snow line. The observations therefore give strong support for our proposed scenario.

3 GIANT PLANETS AND HABITABILITY

The presence of an asteroid belt in an exo-Solar system requires a giant planet. In this section, we first examine the current observations of exosolar giant planets and analyse how special our own Solar system is. We then consider how giant planet migration affects asteroid belts, terrestrial planets and the possibility for life.

3.1 Giant planet observations

In Fig. 2, we show the periastron separation against the mass of the central star for the currently observed giant planets (those with masses $M > 10\,{\rm M_\oplus}$) in the data base exoplanets.org (Wright et al. 2011). We shade the region outside of the snow line. The boundary represents the lower limit of the distances obtained in the numerical snow line models (the lowest dashed line in Fig. 1). A large number of Jupiter-mass planets exist much closer to their host star than Jupiter is to our Sun. It is thought that they formed farther out in the gas disc (outside of the snow line) and migrated inwards

Table 1. Observations of warm dust belts that may be exoasteroid belts.

Source ID	Name	Spectral type	M ($\rm M_\odot$)	$R_{\rm dust}$ (au)	$T_{\rm dust}$ (K)	Age (Myr)	Reference
HD 12039		G3/5V	1.02	$4-6$	109	30	1
HD 13246		F8V	1.06	3.5 ± 0.9	166 ± 18	30	2
HD 15115		F2	1.5	4 ± 2	179 ± 46	12	3
HD 15745		F0	(1.6)	6 ± 2	147 ± 22	12	3
HD 16743		F0/F2III/IV	(3.2)	8 ± 3	147 ± 24	10–50	3
HD 22049	ϵ Eri	K2V	0.82	3 ± 1	$100-150$	850	4
HD 30447		F3V	(1.5)	6 ± 3	159 ± 36	30	3
HD 38678	ζ Lep	A2 IV-V(n)	2.3	3	327	231	5
HD 53143		G9V/K1V	0.8	4	120 ± 60	1	6
HD 53842		F5V	1.20	5.4 ± 1.4	151 ± 24	30	2
HD 86087	HR 3927	A0V	2.44	7	80	50	6
HD 98800		K4/5V	(0.7)	2.2	160	10	7
HD 109085	η Corvi	F2V	1.43	2	180	1000	6
HD 113766		F3/F5V	(1.5/1.4)	4	200	16	6
HD 152598		F0V	1.43	9.3 ± 1.5	135 ± 11	210 ± 70	2
HD 169666		F5	1.35	4.2 ± 0.6	198 ± 13	2100	2
HD 172555	HR 7012	A5 IV-V	2.0	5.8 ± 0.6	200	12	6
HD 181296	η Tel	A0Vn	2.9	5	115	12	6
HD 192758		F0V	(1.6)	7 ± 3	154 ± 31	40	3
HD 218396	HR 8799	A5V	1.5	8 ± 3	150 ± 30	30–160	8, 9
Samples from Morales et al. (2011), median values (range)							
19 solar-type stars		G0V (K0V-F5)	(1.1 (0.8–1.4))		177 (99–220)	270 (40–900)	
50 A-type stars		A0V (B8 -A7)	(2.9 (1.8–3.8))		203 (98–324)	100 (5–1000)	

Note. The masses in brackets have been derived from the spectral type. References. (1) Hines et al. (2006); (2) Moór et al. (2009); (3) Moór et al. (2011); (4) Backman, Marengo & Stapelfeldt (2009); (5) Moerchen, Telesco & Packham (2010); (6) Chen et al. (2006); (7) Low et al. (2005); (8) Chen et al. (2009); (9) Maro-Martín et al. (2010).

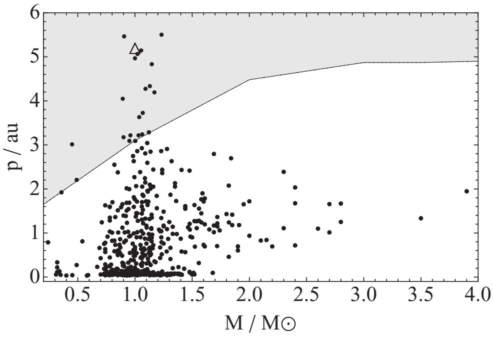

Figure 2. The distribution of observed giant planet periastron separation, p, against the mass of the central star, M. The open triangle shows where Jupiter lies. The shaded region shows the icy region outside of the lower limit to the snow line predicted by our numerical models.

through type II migration (e.g. Lin & Papaloizou 1986). This must have occurred within a few Myr while the gas disc was still present (Haisch, Lada & Lada 2001). In order for a planet not to migrate, we require it to form at just the right time (when the gas is depleted) during the evolution of the protoplanetary disc. Armitage et al. (2002) found that only in about 1–2 per cent of systems does the most massive planet around a solar-type star linger around Jupiter's orbital distance.

During the migration process, a significant fraction of an asteroid belt (if present) would be accreted on to the star, the planet or scattered to large radii (e.g. Fogg & Nelson 2007a). Hence, we would not expect a substantial or compact asteroid belt in these systems. The observed warm dust belts described in Section 2, therefore, likely remain because there has been little or no giant planet migration. Giant planets in these systems must have formed towards the end of the lifetime of the protoplanetary disc. We do, however, note that under special circumstances there could be asteroid belts elsewhere in the system but statistically speaking the most likely place that we have identified is around the snow line.

Out of 520 giant planets shown in Fig. 2, only 19 are outside the snow line. We therefore suggest that less than 4 per cent of these *observed* systems could possibly harbour a compact asteroid belt. This is an upper limit because we have taken the lower limit on the snow line radius (see Section 2) and it is not clear how far out from the snow line giant planets form. For example, Jupiter is twice the radial distance of the snow line in our Solar system and is thought to have only migrated a short distance. Planets close to the snow line, but still outside it, may have undergone more significant migration than Jupiter, which could have disrupted their asteroid belt. The observational results therefore agree with the theoretical models of Armitage et al. (2002) and suggest that our Solar system may be rather special. This argument is based on the detected giant planets, and not on the (clearly difficult) direct detection of asteroid belts. We should note though that selection effects almost certainly affect the statistics, because planets with higher orbital separations are more difficult to detect (see Cumming et al. 2008, for a discussion). Therefore, observations over longer periods of time will be needed to assess accurately how special our Solar system really is (see also Beer et al. 2004).

3.2 Habitable terrestrial planets with a hot Jupiter?

Mars-size bodies are formed through planetesimal accretion on a time-scale of 10^5 yr (Kokubo & Ida 1998). These coagulate on a time-scale of around 30–100 Myr to form Earth-mass planets (Chambers 2001). This is considerably longer than the time-scale to form the giant planets outside the snow line. Thus, the inner giant planets ('hot Jupiters') must have migrated through the habitable zone (which is around 0.95–1.37 au in our Solar system; Kasting et al. 1993) before terrestrial planet formation there was complete. Earth-mass planets could still be found (in principle at least) in orbits inner to the hot Jupiters; however, the hot conditions close to the star are unlikely to produce a habitable planet.

Theoretically, terrestrial planet formation in the habitable zone after the inward migration of a giant planet is possible (Raymond, Mandell & Sigurdsson 2006; Mandell, Raymond & Sigurdsson 2007). Replenishment of the solid disc material after the migration is inefficient (Armitage 2003), but Fogg & Nelson (2007b) found that more than 50 per cent of the solids survive the migration process and are scattered into larger radius orbits, where terrestrial planet formation can resume. The solid material of the scattered disc is diluted, excited and radially mixed. The resulting planets, which may form within the habitable zone, may be more water rich than Earth due to inward mixing from outside the snow line. However, on the basis of the considerations presented in the Section 1, one may speculate that the lack of a compact asteroid belt exterior to the planet's orbit makes the probability for complex life lower.

4 CONCLUSIONS

An asteroid belt may be crucial for the emergence and evolution of life on a planet. Asteroid collisions can deliver water, heavy metals and possibly even primitive life. They can also create large moons which can stabilize planets. While these ideas are clearly speculative, they are sufficiently intriguing to warrant an investigation of the formation and evolution of asteroid belts. We have proposed that asteroid belts, when present, are most likely to approximately coincide with the location of the snow line in protoplanetary discs. Using detailed numerical models of protoplanetary discs, we have shown that the radial distance and temperature of the snow line are indeed entirely consistent with those of observed warm dust, which could correspond to exoasteroid belts.

Giant planets are likely to form outside the snow line, where the solid density increases, thus creating an interior asteroid belt around the snow line where the planetesimals are too excited to fuse. However, less than about 4 per cent of the observed giant planets are found in this region. Inward migration disrupts the asteroid belt. Terrestrial planets may still form from scattered planetesimals in the habitable zone after the migration, but if asteroid belts are indeed necessary for complex life to evolve, then such evolution is unlikely in these systems. On the other hand, a small amount of giant planet migration may be necessary to remove a significant fraction of the initial belt mass because otherwise there would be too many devastating impacts on the planet for life to evolve. Consequently, there appears to be a very narrow 'window of opportunity' of time during which the giant planet should form, in order for the correct amount of migration to take place – potentially making our Solar system even more special.

We do note, however, that the presently existing data may be significantly affected by selection effects. Long-period planets are harder to observe, and in the future more giant planets may be observed outside of the snow line. Based on our scenario, *it is on these systems (with a giant planet outside of an asteroid belt) that we should concentrate our efforts to look for complex life.* Finally, we note that the asteroid belt could prove to be even more important to intelligent life on Earth in the future. On one hand, asteroids could become a source of heavy metals that could be brought back to Earth should our own sources become depleted (e.g. Lewis 1997), and in addition asteroids could also be used as a launch pad for further exploration. On the other hand, clearly asteroid impacts present a danger for the continued evolution of humans on Earth.

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