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The debris disc around τ Ceti: a massive analogue to the Kuiper Belt

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ABSTRACT

An excess of far-infrared emission is seen towards the nearby G8 V star τ Ceti, and this has been attributed to orbiting dust particles generated in planetesimal collisions. A new 850-μm image shows that there is indeed such a debris disc, extending out to ≈55 au (15 arcsec) radius. This is the first disc around a Sun-like star of late main-sequence age to be confirmed by imaging. The dust mass is at least an order of magnitude greater than in the Kuiper Belt, although the dimensions of the systems are very similar and the age of τ Ceti exceeds that of the Sun. Modelling shows that the mass in colliding bodies up to 10 km in size is around 1.2 Earth masses, compared with 0.1 $M_\oplus$ in the Kuiper Belt, and hence the evolution around the two stars has been different. One possibility is that τ Ceti has lost fewer comets from the outskirts of the system, compared with the Sun. Alternatively, a greater number of comets could have been forced out by a migrating planet, compared with the case of Neptune in the Solar system. Notably, the disc of τ Ceti fits the expected decline with time compared to that of the younger nearby star ϵ Eridani. Among these three stars, the Sun would then be the case with the least dust and a 'minimal Kuiper Belt' – a situation which may be beneficial in terms of less bombardment and better stability for life.

Key words: Kuiper Belt – circumstellar matter – planetary systems: formation – planetary systems: protoplanetary discs – infrared: stars.

1 INTRODUCTION

In standard models of planetary formation, the inital circumstellar core of gas and dust flattens into a disc and the solids begin to accrete to form larger bodies, eventually planetary cores and planets. At large distances of tens of au, core growth times are longer and so only a sparse population of bodies up to about the size of Pluto is formed. Small dust particles not incorporated into planets are vulnerable to several processes, including being swept out of the system by radiation pressure, or into the star by drag forces, or destroyed by mutual collisions. However, particles can also be continually regenerated by collisions of km-sized planetesimals, and the latter 'debris' is one of the more readily detectable phenomena around nearby stars.

Debris detection is useful in indicating that bodies at least as large as comets or asteroids were built up around a star, and indeed may be used to trace perturbing bodies of actual planetary mass (Holland et al. 2003). However, the evolution of debris is poorly understood. Since collisions grind down the initial bodies towards smaller and smaller masses, the debris may rapidly become small enough to be removed by the forces listed above. A steep decline of the dust mass might then be expected, and functions as steep in time as t^{-2} (Spangler et al. 2001) have been estimated, with most stars largely dust-free after 400 Myr (Habing et al. 2001).There are some problems with these analyses, because the steepest decline is seen at the end of the primordial disc phase (Wyatt, Dent & Greaves 2003), and masses may be much flatter with time during the main sequence (Greaves & Wyatt 2003). In particular, the detection of dust around some stars much older than 400 Myr (Decin et al. 2000) needs to be explained; many of these are of interest as solar analogues.

The problem with late dust is that collisions may be most frequent when a core grows to 1000 km or so in size (Kenyon & Bromley 2002), massive enough to gravitationally focus nearby smaller planetesimals and increase their collision rate. In the Solar system, the numbers of colliders may have dropped at about 600 Myr, when heavy bombardment of the Earth slowed (Maher & Stevenson 1988). At the present solar age of 4.5 Gyr, collisions appear to be infrequent and the dust mass generated within the cometary Kuiper Belt is only $\sim 10^{-5}$ $M_\oplus$ (Moro-Martín & Malhotra 2003). The presence of much higher dust masses around stars similar to the Sun would therefore indicate a significant diversity in initial conditions or evolution.

In this paper, we present observations towards the closest single G-type star of comparable age to the Sun, τ Ceti (HD 10700, HR 509, GJ 71). This G8 dwarf is at a distance of 3.65 pc, and has a

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★E-mail: jsg5@st-andrews.ac.uk (JSG); wyatt@roe.ac.uk (MCW); wsh@roe.ac.uk (WSH); dent@roe.ac.uk (WRFD) far-infared excess at 60–170 μm (Aumann 1985; Habing et al. 2001). If arising from grains around a micron in size, the excess could represent a mass as small as 2×10^{-4} $M_\oplus$ (Habing et al. 2001). However, these *ISO* observations were made with resolution of at best ≈ 50 arcsec, and so background sources could be mis-identified as a disc signature; this has in fact occurred in the case of the similar star 55 Cnc (Jayawardhana et al. 2002). In this paper, we show the first example of a disc excess around a Sun-like star to be confirmed by higher resolution imaging.

2 OBSERVATIONS

The Submillimetre Common User Bolometer Array (SCUBA) camera (Holland et al. 1999) at the James Clerk Maxwell Telescope was used to observe τ Ceti in 2001 September and November, for a total integration time of 13.3 h. The primary wavelength was 850 μm, with 450-μm imaging observations made simultaneously but with lower atmospheric transparency. At 850 μm the full width at half-maximum beam width was 15.3 arcsec and the zenith atmospheric transmission was 0.16 to 0.29. The data were calibrated against Mars, Uranus and the secondary sources CRL 618 and HL Tau, with results agreeing with standard values and internally consistent to ± 7 per cent. The telescope pointing performance was somewhat erratic, with a mean drift of 3 arcsec and worst-case of 7 arcsec during the 21 individual maps; linear corrections have been applied but in any case these drifts are negligible compared with the resolution of the final image.

Standard 'jiggle map' reduction was used (Jenness et al. 2002), and the final map includes weighting of each bolometric detector by its intrinsic noise, and the 21 individual maps by their mean noise. The photospheric signal of 1.2 mJy was subtracted using a scaled map of a point source; this value was extrapolated from the 12–60 μm *IRAS* and *ISO* stellar fluxes or predictions (Habing et al. 2001; Laureijs et al. 2002) and has an error of ± 0.1 mJy from differences between data sets. The final map has 2-arcsec pixels (slightly smaller than the 3-arcsec sampling) and has been smoothed using a 12-arcsec Gaussian. Combining this with the beam size, the effective resolution is 20 arcsec or 70 au. The noise was measured from the deviations over blank parts of the field, and is dominated by low-level ripple. Over the whole field the pixel variations correspond to 0.75 mJy per effective beam area, but the scatter between blank regions of disc-like size is lower, with a 1σ dispersion of 0.6 mJy. A correction for mean non-zero background level (attributed to imperfect removal of sky emission) added 0.7 mJy of flux within the disc area.

3 RESULTS

The 850-μm image towards τ Ceti is shown in Fig. 1. There is a symmetrical feature oriented approximately north–south which is centred very close to the star (diamond symbol). This appears very similar to, for example, the disc seen nearly edge-on around Fomalhaut (Holland et al. 2003), and we therefore identify this as a debris disc around τ Ceti. It is unlikely that this is a background object, because although there is an approximately 75 per cent chance of a field of this size containing a distant source of around 5 mJy (Scott et al. 2002), it is unlikely this would be both centred very close to the star and also elongated symmetrically about it. There are a number of other features in the image which are most likely such background dusty galaxies, as they have no catalogued counterparts at other wavelengths. The count of ≈8 sources of 1.7–3 mJy beam^{-1} exceeds by about 50 per cent the peak numbers measured in submillimetre surveys (Scott et al. 2002), but as the galaxies tend to be clustered this is not a serious objection. If lying at moderate redshift, these sources would have thermal emission peaking in the short submillimetre: for example, blackbody grains at 30 K would peak at 350 μm instead of 100 μm, if at a typical redshift of 2.5 (Chapman et al. 2003). These sources may therefore have contributed negligible flux in the ISOPHOT 60-μm band.

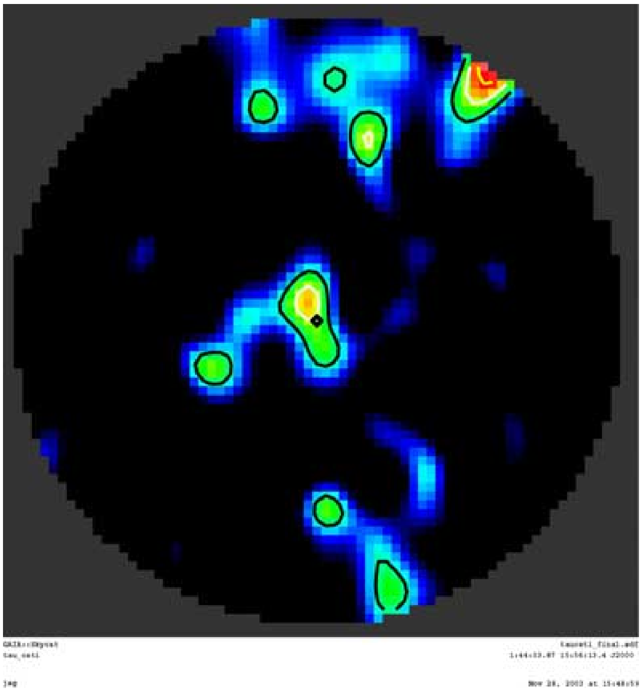

Figure 1. 850-μm image of τ Ceti, smoothed to 20-arcsec resolution. The stellar position at the epoch of the observations is marked by a diamond, and was $01^h44^m03^s.87$, $-15°56'13''.4$ in J2000 coordinates. The colour scale ranges from 1.5 to 4.9 mJy per 20-arcsec beam (0.02 to 0.065 mJy per 2-arcsec pixel for purposes of integration by area), corresponding to 2σ–6.5σ where the 1σ noise is estimated from the level of background variations. The contours are 4σ, 5σ and 6σ, in respectively black, white and yellow in the online version of the article on *Synergy*. The field of view shown is 70 arcsec in radius.

3.1 Disc structure

The total disc flux is 4.6 (±0.6) mJy, within an ellipse of major and minor axes 36.5 × 19.5 arcsec angled 6° east of north (anti-clockwise in the image). The error is derived from background variations as described above, and the disc detection is significant at the 7.5σ level. The ellipse is closely matched to a 2σ contour, but adopting a larger region would increase the total flux by only up to about one-third. The northern and southern ends of the disc do not differ significantly in flux, at 2.5 and 2.1 mJy respectively within beam-sized circles.

These disc dimensions correspond to 130 by 70 au, or a maximum radius of ≈ 55 au once deconvolved from the beam. The minor axis is unresolved, but if the contour were up to 5 arcsec wider (from -1σ changes in flux density), then the minor axis radius could be up to 25 au. Assuming a geometrically thin disc, the inclination is then 60°–90°, close to edge-on. However, the star seems to be viewed more pole-on as the observed rotational velocity ($v \sin i$) is only 0.4 ± 0.4 km s^{-1} (Saar & Osten 1997). Combined with the known stellar rotation period and radius (Saar & Osten 1997;

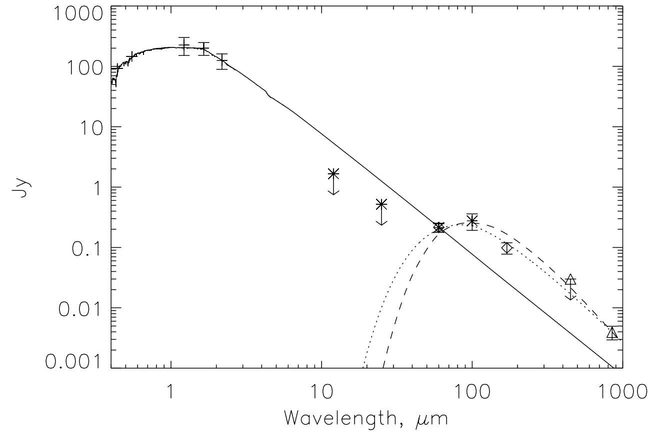

Figure 2. Spectral energy distribution. Plus symbols show optical and near-infrared stellar fluxes (from SIMBAD and 2MASS) and the solid line is a Kurucz atmosphere with $T_{\rm eff}$ = 5430 K. Other points are from SCUBA (triangles), *IRAS* (asterisks) and *ISO* (diamonds) with the colour-corrected stellar fluxes subtracted. Error bars show 1σ uncertainties and downward arrows 3σ upper limits. The dotted line is a modified blackbody fit from dust at 60 K with 0.5 opacity index in the Rayleigh–Jeans tail; the dashed line fit is for a collisional cascade (see text).

Di Folco et al. 2004), the implied inclination of the stellar equator is $\approx 0°$–$40°$ from the sky plane. Thus the disc results are marginally inconsistent with the stellar equator and disc plane being aligned, but could be reconciled with a slightly larger error bar ($v \sin i$ above 1.05 km s^{-1} implies $i > 60°$). It is also possible that the peaks are features within a more pole-on disc, as in the case of Vega (Holland et al. 1998), where there are circular contours surrounding two peaks. Because the τ Ceti emission is much fainter than that of Vega, such a disc component would be hard to detect above the background limits.

3.2 Disc parameters

Fig. 2 shows the spectral energy distribution of τ Ceti and its disc, as defined by the SCUBA results, the detections of 60- and 170-μm excesses with *ISO* (Habing et al. 2001), and a reanalysis of the *IRAS* 60- and 100-μm data using SCANPI (http://irsa.ipac.caltech.edu). The new *IRAS* fluxes (including the star) are 500 ± 34 and 360 ± 84 mJy at 60 and 100 μm respectively, while Habing et al. (2001) measured 433 ± 37 mJy at 60 μm with *ISO*. The *ISO* 60-μm beam was smaller than that of *IRAS*, so the similar fluxes suggest that the sources around the edge of the SCUBA field contribute little far-infrared signal. An extra constraint is the SCUBA 3σ limit of ~30 mJy at 450 μm; this was set by background structure seen at about the 10-mJy level.

The 60–850 μm excesses can be fitted with dust at a single temperature of 60 K, and an opacity index of 0.5 beyond a wavelength of $\lambda_0 = 100$ μm. This index applies because grains may be greybodies, i.e. not perfectly efficient in re-emitting absorbed radiation. The value of 0.5 is slightly lower than the 0.8 measured in debris discs around the nearby stars ϵ Eri, Vega and Fomalhaut (Dent et al. 2000; Holland et al. 2003); near-zero indices imply grains that are close to blackbodies and much larger than interstellar grains. The far-infrared excesses can be fitted as entirely from the disc with negligible contribution from the background objects.

A good single-temperature fit suggests that the dust may lie in a ring rather than a broad disc (a radius range imposes a temperature range if the grains are in thermal equilibrium with stellar radiation). The lack of 25-μm emission implies an inner cut-off to the disc, and Laureijs et al. (2002) infer that there is no detectable dust warmer than ~85 K in their *ISO* 25-μm study. In equilibrium with the star this implies few grains inside 10 au, while the SCUBA image constrains the dust to lie at not more than 55 au. For a typical distance of about 40 au, a dust temperature of 40 K would be expected. Since greybodies will be warmer than blackbodies at the same distance, the above result of 60 K for an opacity index slightly above zero is reasonable. If the far-infrared fluxes were instead attributed to background objects, the limiting fit would be a blackbody through the 850-μm point set to the coolest dust temperature at the largest dust radius of 55 au. For the resulting temperature of 34 K, dust mass estimates would increase by a factor of ~2.

Using the 850-μm flux and a temperature of 60 K, and assuming an opacity ≈ 1 cm^2 g^{-1} (Greaves et al. 1998), the dust mass is estimated at 5×10^{-4} M$_\oplus$. This is slightly higher than the 2×10^{-4} M$_\oplus$ from *ISO* data alone (Habing et al. 2001). [The 25-μm limit suggests $\lesssim 2 \times 10^{-5}$ M$_\oplus$ of warm dust (Laureijs et al. 2002), or less than ~5 per cent of the total mass lying inside 10 au.] The advantage of the submillimetre result is that it does not depend on an assumed grain size, and the main uncertainty is in the adopted dust opacity: changes in grain properties vary the opacity by only factors of ~2 (Ossenkopf & Henning 1994).

4 DISCUSSION

This is only the second late-type star for which debris has been imaged. The previous example is ϵ Eridani (Greaves et al. 1998), which is similarly distant at 3.2 pc but a less close solar analogue, of type K2 V and with an estimated age of 0.73 ± 0.2 Gyr (Song et al. 2000). In contrast, τ Ceti has been shown from stellar interferometry (Pijpers et al. 2003; Di Folco et al. 2004) to be $\approx 10 \pm 0.5$ Gyr old, *older* than the Sun. These two stars are in fact the only single dwarfs of roughly solar spectral type to lie within 5 pc of the Sun, so a comparison of their dust properties is of interest. Placing the three stars in context, the Sun and τ Ceti have similar-sized collisional belts while that of ϵ Eri extends twice as far; the dust temperature of τ Ceti is 70 per cent higher than that of ϵ Eri (from the former's higher stellar luminosity and smaller disc); and there is a 20-fold drop in dust mass between these two stars but with the Sun at intermediate age being still lower in mass. Although ϵ Eri may possibly mirror the early stages of the Solar system, τ Ceti demonstrates that later evolution can be very different.

The dust around τ Ceti is located in a region similar to the Kuiper Belt in the Solar system, where the bulk of the detected bodies orbit at 35–50 au. The mass of these Solar system comets is around 0.1 M$_\oplus$ (Gladman et al. 2001), mostly in large bodies tens of kilometres in size. The mass in dust particles is small but uncertain, and a difficulty is that different models present mass summations over different ranges of particle size. Hence more direct methods have been sought to compare the Kuiper Belt dust mass with that of τ Ceti. First, Landgraf et al. (2002) use data on impacts on to the *Pioneer* spacecraft, sensitive to bodies of a few microns to a few millimetres. Their estimated dust production rate is 5×10^7 g s^{-1}, which combined with their particle lifetime estimate of 10^7 yr implies a total mass of $\sim 3 \times 10^{-6}$ M$_\oplus$, two orders of magnitude less than for τ Ceti. Secondly, Fixsen & Dwek (2002) show *COBE*/FIRAS data that can be used to estimate the submillimetre flux of the Kuiper Belt. Their upper limit at 800 μm[1] is

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[1] This wavelength is close to the SCUBA 850-μm passband and is preferable to the FIRAS 850-μm signal which includes Galactic carbon monoxide emission at 867 μm.

<0.03 MJy sr^{-1}, which sums to <0.016 MJy for the belt they consider of about 5° height. Morbidelli et al. (2004) show that approximately half of the Kuiper Belt population lies within ±5° inclination with the other half at higher angles; we therefore scale the Kuiper Belt limiting flux up by a factor of 4 to <0.065 MJy. When translated from ≈45-au to 3.65-pc distance, this is equivalent to <0.23 mJy for a Kuiper Belt-like dust signal around τ Ceti. The actual value for the τ Ceti dust disc is 4.6 mJy so, assuming similar grain properties, the flux ratio implies that the disc of τ Ceti is at least 20 times dustier.

The generation of dust in collisions has been modelled as in Wyatt & Dent (2002). The dust is assumed to be solid grains composed of a mixture of amorphous silicate and organic refractory material. The grain emission properties were calculated using Mie theory and the disc emission fitted (Fig. 2) assuming a collisional cascade size distribution extending down to a smallest size of $D_{\min}$. The observed disc size in the submillimetre of ∼40 au constrains $D_{\min}$ to be 20 μm, above the radiation pressure blowout limit of 1 μm, similar to the result found for the ϵ Eri disc (Sheret, Dent & Wyatt 2004). Tracing the size distribution back to the larger planetesimals which are colliding to replenish the dust, and considering their collisional lifetimes, we find that for the age of τ Ceti of ≈10 Gyr (Di Folco et al. 2004), the largest colliders are ∼50 km in diameter and the total mass of the collisional cascade is 1.2 $M_\oplus$. This is in strong contrast to the Solar system, where the collisional cascade of the Kuiper Belt is also inferred to start around 50 km, but contains only ∼0.1 $M_\oplus$ (Gladman et al. 2001). Hence the population of planetesimals around τ Ceti is inferred to be about an order of magnitude greater than in the Kuiper Belt.

This is surprising given that the two stars are alike: both are late-type dwarfs (the Sun is G2 V and τ Ceti G8 V) and on the mid- to late main sequence. The evolution of these systems might therefore be expected to be similar, but τ Ceti appears to retain a much greater cometary population. The question then arises of which system is more typical of stars in general. Within 5 pc, which is about the threshold for confirming moderate masses of cold dust, there are only five G to mid-K systems and of these three (α Cen, 61 Cyg and ϵ Ind) have multiple stellar components inside 100 au that can tidally strip discs. This leaves only τ Ceti and ϵ Eri, which are both much dustier than the Solar system.

4.1 Comparison with models

A widely held view is that substantial amounts of debris are characteristic only of young main-sequence stars, over an era roughly matching the Earth's period of heavy bombardment (Habing et al. 2001). However, τ Ceti is part of an emerging population (Decin et al. 2000; Greaves et al. 2004) of mature solar-type stars with large debris masses that needs to be explained. Kenyon & Bromley (2004) have modelled the production of dust around stars on the main sequence, and found that collisions may generate debris even at late times of several Gyr. In their simulations, this is because of a prolonged slow growth phase of planetary cores; once they reach about 1000 km in diameter (similar to Pluto) they gravitationally focus the orbits of smaller bodies, increasing their collisional rate and generating dust. The growth time-scale has a strong dependence on radius ($t \propto a^3$, where a is semi-major axis) and so a large dust ring can be seen at late times. However, since the τ Ceti dust extends out only about as far as the Kuiper Belt, it is difficult for the models to reproduce this as late as 10 Gyr. A very low initial mass of solids in the primordial disc would slow the evolution, but from the relations in Kenyon & Bromley (2004) this would have to be only ∼ 3 $M_\oplus$ – in which case, the late-time debris mass would also be proportionally small.

It is more likely that τ Ceti is in the decline phase rather than having recently formed dust. Kenyon & Bromley (2004) find that at late times the dust mass declines as a power law of slope in the range t^{-1} to t^{-2}. In this case, τ Ceti can be regarded as a natural descendant of ϵ Eri, assuming only that they are both past the dust production peak. The ratio of ages is ≈13 so the dust mass ratio should be about 1–8 per cent with these power laws. In fact τ Ceti has 5 per cent of the 0.01 $M_\oplus$ of dust around ϵ Eri (Greaves et al. 1998), consistent with a decay of around $t^{-1.2}$. However, the Kuiper Belt is then *not* a natural descendant of the ϵ Eri system, because at 4.5 Gyr the Solar system dust mass would be predicted to exceed 10^{-4} $M_\oplus$, even taking the steepest decline of t^{-2} and the youngest ϵ Eri age bound (Song et al. 2000).

We briefly consider two hypotheses for the diversity of the τ Ceti debris disc and the Kuiper Belt. First, the Kuiper Belt is itself enigmatic because as much as 99 per cent of the material seems to be 'missing', if the density of the primordial disc needed to form the planets is extrapolated out to ∼ 50 au (Morbidelli et al. 2004). It is possible that many of the original comets were ejected, for example by a mechanism such as a close stellar 'fly-by' – in this case, τ Ceti and ϵ Eri could be regarded as systems that have *not* suffered such an event and so retain most of their outer planetesimals. This explanation could accommodate the order-of-magnitude higher mass in comets around τ Ceti, but has the disadvantage that a close stellar encounter with the Sun would be rare. Secondly, Levison & Morbidelli (2003) have suggested that there is no deficit in the Kuiper Belt: this zone beyond ≈35 au could originally have been empty but is now sparsely populated by bodies pushed outwards by the migration of Neptune. Objects are carried out more efficiently by a planet if its migration is smooth (a detail that depends on how many lunar-like bodies cross the orbit of the planet), or if migration is slow (Wyatt 2003). For τ Ceti, either the efficiency could have been greater than the ∼1 per cent of bodies moved in the Solar system (Levison & Morbidelli 2003), or the mass reservoir initially outside the orbit of the planet could have been higher, producing more dust-generating collisions. The drawback of this model is that it requires the primordial discs of both the Sun and τ Ceti to have been quite small, less than 50 au, while the debris disc of ϵ Eri extends out to 100 au (Greaves et al. 1998) and primordial dust discs frequently exceed this (Kitamura et al. 2002).

We stress that other hypotheses may also explain the large dust mass around τ Ceti compared with the Sun. Comparing only with Kuiper Belt models, the comet zone of τ Ceti could be either less depleted or more efficiently populated by migration, but both ideas have weaknesses in requiring an unusual property or event relating to the disc. The migration model also removes any link with the younger star ϵ Eri, as the late-time appearance of any system would depend on its early migration history. Indeed, dust generation must be stochastic at some level, as it arises from the break-up of individual comets, so any one disc would vary in appearance over time. Until more systems have been imaged, there are only these three examples of collisional discs around Sun-like stars, and, while no one model explains them all, it is difficult to say which of the three discs might be exceptional.

5 CONCLUSIONS

The debris disc around τ Ceti has a dust mass at least an order of magnitude more than in the Kuiper Belt. Since dust is removed quite rapidly by drag and radiation forces, this material must have been generated recently by collisions among cometary bodies. This parent population is estimated to include 1.2 Earth masses in objects up to 50 km in size, compared with $\sim$0.1 $M_\oplus$ in the Kuiper Belt. The dust mass around τ Ceti is 20 times less than around the younger star ϵ Eri, consistent with the models of Kenyon & Bromley (2004) if both systems are post-peak in dust production. However, the Solar system falls below the relation of mass and age for the other two stars. It is possible that the Kuiper Belt has suffered a disruptive event so that it now has unusually few comets, or else that the details of planetary migration affect the final cometary population and location. Either of these models could potentially explain an order of magnitude more collisionally produced dust around τ Ceti compared with the Sun, over a zone of similar size. The disruption model would leave the Sun as anomalous, compared with the evolutionary link between τ Ceti and ϵ Eri, while the migration model has random elements that imply that debris discs could differ substantially between any two stars.

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