Mon. Not. R. Astron. Soc. **000**, 1–8 (2009) Printed 29 January 2010 (MN LaTeX style file v2.2)

Debris discs and comet populations around Sun-like stars: the Solar System in context

J. S. Greaves[1]* & M. C. Wyatt[2]

[1]*SUPA, Physics & Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS, UK*

[2] *Institute of Astronomy, University of Cambridge, Cambridge CB3 0HA, UK*

Accepted 2009. Received 2009; in original form 2009

ABSTRACT

Numerous nearby FGK dwarfs possess discs of debris generated by collisions among comets. Here we fit the levels of dusty excess observed by Spitzer at 70 μm and show that they form a rather smooth distribution. Taking into account the transition of the dust removal process from collisional to Poynting-Robertson drag, all the stars may be empirically fitted by a single population with many low-excess members. Within this ensemble, the Kuiper Belt is inferred to be such a low-dust example, among the last 10 % of stars, with a small cometary population. Analogue systems hosting gas giant planets and a modest comet belt should occur for only a few per cent of Sun-like stars, and so terrestrial planets with a comparable cometary impact rate to the Earth may be uncommon. The nearest such analogue system presently known is HD 154345 at 18 pc, but accounting for survey completeness, a closer example should lie at around 10 pc.

Key words: planetary systems – circumstellar matter – infrared: stars

1 INTRODUCTION

Impacts pose a hazard to life on Earth, especially in the case of an event energetic enough to destroy much of the surface crust and oceans (Zahnle et al. 2007). The most destructive impacts are associated with comets rather than asteroids, as the former hit at high speeds when infalling from the Kuiper Belt region (Jeffers et al. 2001), but the present-day cometary impact rate is low, largely because most of the primordial bodies have been dispersed (Morbidelli et al. 2003). This is thought to have occurred in the first Gyr of the Sun's life, when Jupiter and Saturn crossed a mean motion resonance, destabilising the gas giants so that Saturn had close encounters with Uranus and Neptune. The expansion of their orbits perturbed the primordial Kuiper Belt (Gomes et al. 2005), producing the Late Heavy Bombardment of the Earth at around 700 Myr, after which the comet population was greatly depleted and the impact frequency has been much lower. However, the presence of the gas giants is still significant today, as dynamical interactions can bring comets into the inner Solar System – Horner & Jones (2008) have recently shown that the impact rate on the Earth would vary significantly if the mass of Jupiter were different.

Thus, in extrasolar systems we may expect that the number of comets and the architecture of the giant-planet system will strongly affect the impact rate on any terrestrial planets present. Direct evidence of impacts in the inner systems comes from detections of dust grains at temperatures of a few hundred Kelvin, representing break-up debris from parent planetesimals. Such detections via a mid-infrared excess signal above the stellar photosphere are rare, but this does not imply that inner system planetesimals and planetary impacts are sparse, as the debris lifetime at a few AU is short (Wyatt 2005). Less directly, we can examine the far-infrared debris signatures to assess the numbers of bodies colliding within the cool outer comet belts, and consider the influence of gas giants in perturbing comets inwards to where they threaten terrestrial planets.

Here we use the results of recent volume-limited surveys of Sun-like stars with Spitzer by Trilling et al. (2008) and Beichman et al. (2006) to study the dustiness of Solar-analogue systems, via the predominantly 70 μm detections of excess above the stellar photospheres. Various analytical models, as reviewed by Wyatt (2008), predict far-infrared dust luminosities as functions of initial size and mass of the planetesimal disc and the age of the host star. Thus the excesses detected by Spitzer can be related to the ensemble of populations of comets per star. We can then place the Sun's Kuiper Belt, for which there are measurements of the numbers and distribution of comets and dust particles, in the context of similar stars. For example, other systems are known that are hundreds of times dustier than the Solar Sys-

* E-mail: jsg5 at st-andrews.ac.uk

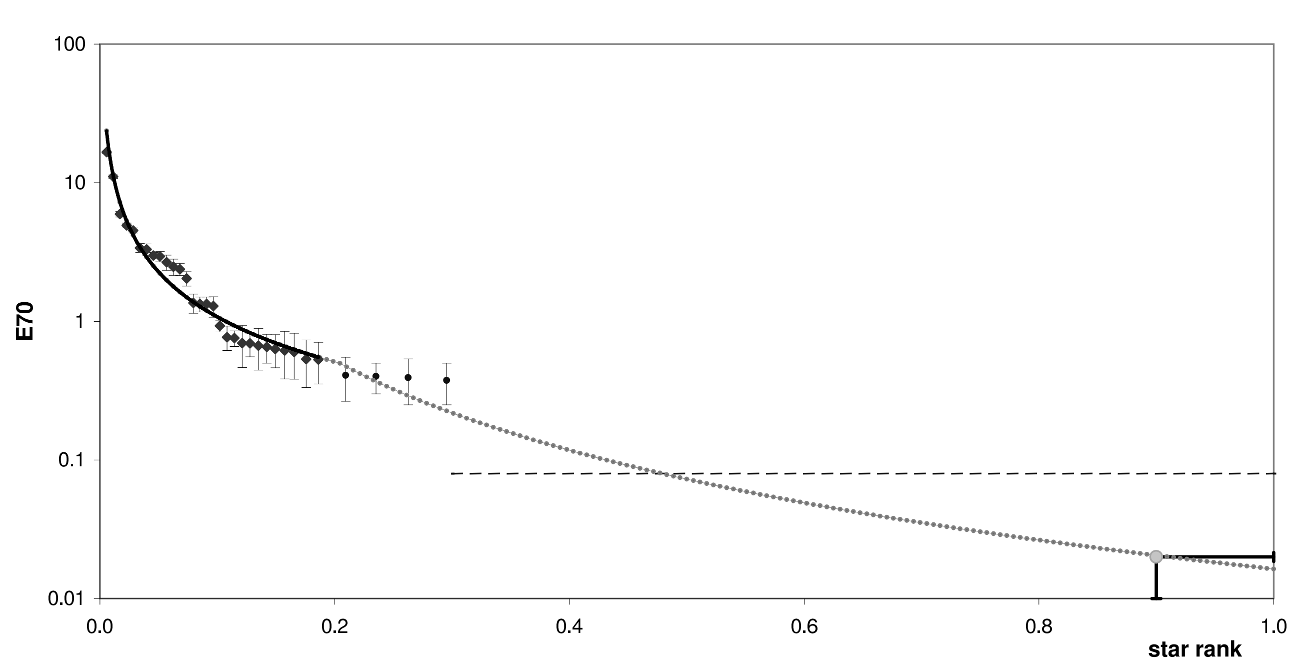

Figure 1. Sun-like stars in order of decreasing 70 μm excess (y-axis). The rank on the x-axis is the star's number (e.g. 1 for the most dusty) divided by the number of stars surveyed. Upper limits are not plotted. The diamonds show contiguous debris detections while the four points plotted with circles have intervening systems with only upper limits in E_{70}; the spacing of these sparse detections is derived as described in section 3.1. The black curve is a power-law fit for stars of E_{70} down to 0.5, excluding the four sparse detections of lower excess. The grey line is an extrapolation to lower excesses including dust removal theory (section 3.4), not a fit to the four circle symbols. The dashed line shows the 2.5σ upper limit to the net E_{70} for stars where detections beyond $x = 0.3$ could be made (section 3.2). The circle symbol (far right) is the position of the Sun in the ensemble, derived from its maximum estimated dust level (section 4.1) and plotted at its corresponding lowest rank on the grey curve. The bars indicate that the Sun may be less dusty and so of higher rank.

tem; dustier at greater age than the Sun; or have much larger debris belts. Viewed externally as a debris disc, the Kuiper Belt would be faint, a result which motivates this study to answer the question of whether the planet and planetesimal population around the Sun is unusual, and whether this has any role in impacts on the Earth and the evolution of life.

2 DATA

Two major unbiased surveys of nearby Solar analogues have been made with Spitzer, with debris detection rates of ≈15 % at 70 μm, for fractional excesses of a few tenths or more above the photosphere (Trilling et al. 2008; Beichman et al. 2006). The FGK targets in these two samples are complementary and extend out to ∼ 30 pc from the Sun; a further survey (Kim et al. 2007) will complete much of this volume. We neglect here results from the FEPS project (Hillenbrand et al. 2008; Carpenter et al. 2009; Meyer et al. 2008) where stars were selected by age, and so there is a trend of lower sensitivity for younger and thus rarer and more distant stars. The published nearby-volume samples also have some biases that are inherited from the goals of the original proposals, with more luminous stars, hosts of giant planets and single stars over-represented compared to their true proportions among Sun-like stars.

Only 70 μm data of high quality from Trilling et al. (2008) and Beichman et al. (2006) are discussed here, tracing cool dust at tens to hundreds of AU from the host star. The photospheric signal was not detectable with 3-sigma confidence in all the stars, so there is a potential bias where faint stars rise above the detection threshold of *total* flux only in cases of large excess. To avoid this, we selected only the objects with $F_*/\delta F > 3$, where F_* represents the photosphere and δF is the noise in the flux measurement. This selection includes 176 stars from the two combined surveys, after also eliminating a number of M-dwarfs from Beichman et al. (2006). The excesses are then defined as $E_{70} = F_{dust}/F_* = (F_{total} - F_*)/F_*$. All further analysis uses the fluxes and errors listed by Trilling et al. (2008); Beichman et al. (2006) along with their other tabulated quantities, such as estimates for stellar ages.

The survey papers identify debris systems as those with E_{70} at 3σ confidence, i.e. $\chi_{70} = F_{dust}/\delta F \geqslant 3$, here comprising 27 stars. Here we add 6 more candidate systems of slightly lower significance. A tabulation of all 176 E_{70} values, in order of χ_{70}, shows that *negative* outliers extend down to -2.5σ, and this distribution is quite symmetric, with 70 stars of $0 \leqslant \chi_{70} \leqslant +2.5$ versus 73 of $-2.5 \leqslant \chi_{70} < 0$. Further, this χ_{70} distribution is close to a Gaussian centred on a null value, with mean and sigma of -0.03 and 1.2 respectively. We thus adopt here as candidate debris systems all those with $> +2.5\sigma$ significance, and estimate that the chance of a false positive is $\lesssim 1.5$ % per star, given that < 1 more extreme outliers appear among 73 negative results. With this new selection criterion, there are 33 systems identified here as debris hosts[1] , or 19 % of the stars observed.

[1] Those of 2.5-2.9σ confidence are HD 39091, 55575, 69830,

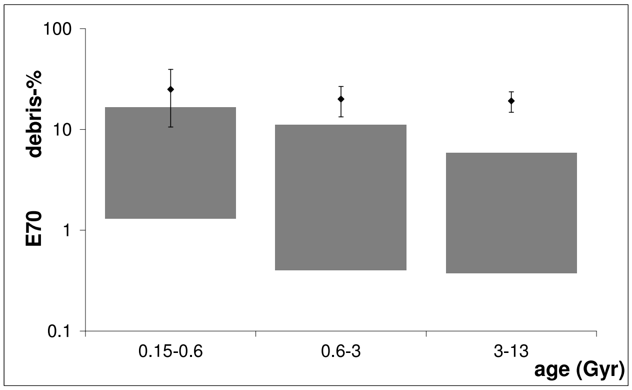

Figure 2. Debris properties of the sample, in logarithmic age bins. The grey bars show the minimum-to-maximum E_{70} within each bin, and the points (and Poisson error bars) indicate the percentage of stars with debris. The number of systems detected (observed) in each age bin from left to right is 3 (12), 9 (45) and 19 (99), with 18 stars having no tabulated ages.

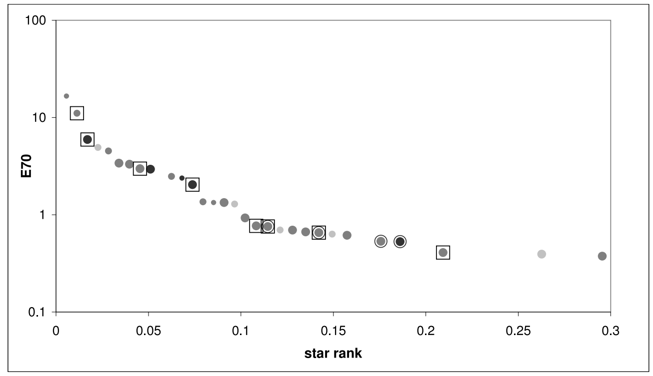

Figure 3. Detected debris systems, showing stellar properties. Small, medium and large symbols correspond to the early, mid and late age-bins respectively of Figure 2, and light and dark grey shadings pick out the most and least luminous stars (early-F and K types respectively). Points within circles are systems hosting giant planets (from the Extrasolar Planets Encyclopedia) and those within squares have multiple stars (from the Catalog of Components of Double and Multiple Stars).

3 ANALYSIS

3.1 Detected population

Figure 1 plots the 70 µm excesses of the stars where debris is identified, ordered by a fractional 'rank'. The rank is formulated as the number of the star in order of decreasing E_{70}, divided by the total number of stars (176). It is equivalent to the fraction of stars with equal or higher E_{70} than the current plotted point. However, beyond a rank of 0.1, not all the stars were observed to sufficient depth to detect the corresponding E_{70} of approximately 0.8 and below, if such excesses are present. This tendency is in fact implicit in the initial selection, as $\delta E_{70} = \delta F/F_*$ and so where $F_*/\delta F$ approaches 3, only $E_{70} > 0.83$ can be detected with 2.5σ confidence. In this regime, there are four debris detections (circles in Figure 1) that are interleaved with upper limits of similar E_{70}, but the ranks of the non-detections can not be determined as the true debris levels are unknown. However, plotting these four points as contiguous ranks causes an artificial downturn in the trend of excess, because similar systems should occur in this region but were not actually observed deeply enough to be detected. Thus for these four points, estimated ranks are plotted, by increasing the step on the x-axis from 1/176, to 1/176 multiplied by a scale factor of (number of stars still to be counted) divided by (number of stars where the next E_{70} could be detected). These stars with $E_{70} \approx 0.4$ were numbers 30 to 33 in order of decreasing dustiness, and their original ranks of 0.17 to 0.19 (30/176 to 33/176) have been increased to 0.21 to 0.30.

The excesses observed range from 17 down to 0.4, although only about one in five stars was observed deeply enough to detect debris at this lower bound. The minimum detectable excess for Spitzer, where generally the dust and star lie within the same telescope beam, is set by uncertainty in the photospheric predictions plus errors in the shorter-wavelength data used for extrapolation. Dispersions in 24 µm data of around 5 % are observed (Beichman et al. 2006) and these are likely to be the minimum inherited errors when attempting to detect low levels of debris at 70 µm.

There is no strong trend of level or incidence of debris with particular stellar properties. For example, there is little trend with age, as already noted by e.g. Trilling et al. (2008); Beichman et al. (2006); Greaves & Wyatt (2003). Figure 2 shows the sample divided into three broad bins each spanning a factor of ≈ 4 in age (to minimise errors from poorly-dated objects). The detection rate is essentially flat with age over the entire main sequence, while maximum dustiness declines mildly with age – a similar decline has been seen for 70 µm excesses of A-type stars (Su et al. 2006). These trends agree with recent evolutionary models as summarised by Wyatt (2008), where each system's dustiness declines slowly with time as the parent population of colliding bodies is ground away. If the initial planetesimal discs have a wide range of radii and masses, then there is a wide range of excess values at any one age, and the detection rate is rather constant with time if the upper envelope of maximum dust flux is well above the detection limit (Greaves & Wyatt 2003).

Further, there are only weak trends associated with other stellar properties, such as luminosity, binarity and the presence of giant planets (Beichman et al. 2006; Bryden et al. 2006; Trilling et al. 2007). Figure 3 replots the debris hosts of Figure 1 with symbols denoting these properties, and no obvious trends are visible. In further analysis, all the stars are therefore treated as a single population.

3.2 Trend in debris level

The ranked plot (Figure 1) shows that the excesses form a rather smoothly declining distribution, dominated by lower values of E_{70}. The steep slope can explain how the rate of far-infrared debris detection among Sun-like stars has risen with improvements in sensitivity with successive instruments, namely the IRAS, ISO and Spitzer missions. For example, a typical G-dwarf photosphere at 15 pc has a flux of approximately 30 mJy at 60 µm (Habing et al. 2001), while the IRAS all-sky survey could detect signals of around

114613, 173667 and 222237; HD 69830 is a confirmed debris system with shorter-wavelength excesses (Trilling et al. 2008).

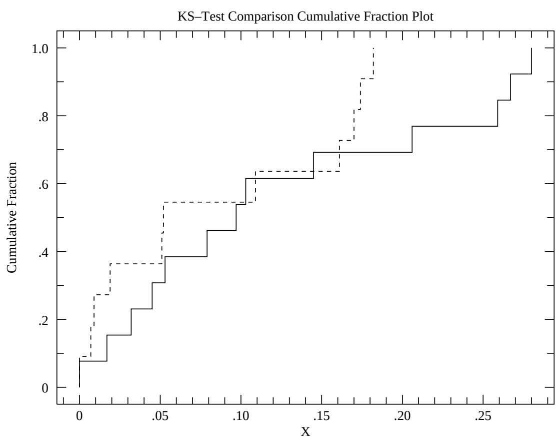

Figure 4. Cumulative distributions of measured E_{70} (X axis) for 24 upper-limit systems discussed in the text. These have small E_{70} errors of $\leqslant 0.15$ and so the distribution is a guide to whether a net positive excess may be present. Positive values (solid line) are compared to negative values that have been multiplied by -1 (dashed line).

200 mJy (Wyatt 2005) and the corresponding limit for ISO was around 90 mJy (Decin et al. 2000). Thus IRAS and ISO could detect $E_{60} \sim 6$ and 3 respectively. Of the stars plotted in Figure 1, we would then expect about 3 bright examples to be discovered by IRAS, and HD 139664, 48682 and 109085 were actually found. Subsequently, ISO could have discovered ~ 6 less-dusty systems, while the sparse surveys actually undertaken added two discoveries[2], HD 30495 and 17925

The large sensitivity improvement with Spitzer has more than tripled the discoveries of debris systems among these nearby stars, suggesting that more fainter examples remain to be discovered. However, debris levels in the presently undetected population are inferred to be small on average. Aumann & Good (1990) suggested that a net excess of ~ 0.05 might be present, from IRAS 60 μm data for G-stars within 25 pc. The Spitzer 70 μm data now explore this regime lying at the right of Figure 1, although individual excesses are still not detected. For example, there are 24 stars with Spitzer observations deep enough that excesses ranging from 3 % to 37 % could have been detected, if such dust levels were actually present in these systems. (Here we neglect the uncertainties due to calibration and just consider signals of 2.5 times the noise level.) These stars are part of the population at star-rank > 0.3 in Figure 1, and none of them has a significant measurement of excess, but the data are deep enough that a tendency to mildly positive values can be searched for. In particular, stacking the data can show if there is evidence for an average non-zero dustiness that is not apparent in each individual noisy observation. Averaging the measured E_{70} for these 24 stars we find 0.03 ± 0.02 for the mean value and standard error on the mean[3]. This is not a significant detection of net excess, so the suggestion of a typical excess of 0.05 by Aumann & Good (1990) (at 60 μm) can not be confirmed. However, it does allow all systems to be slightly dusty, or some to have modest excess while others are dust-free, as well as the possibility that all are dust-less. Among these 24 targets there may in fact be a slight skew towards more positive E_{70} measurements (Figure 4), but a Kolmogorov-Smirnov test finds a probability of only 54 % that this positive tail are from a different (i.e. debris disc) population. Therefore there is as yet no conclusive result, but this does not rule out many low-dust systems. As a small excess is characteristic of the Solar System, attempting to infer the underlying population is useful to put the Sun in context.

[2] Five other fainter debris systems in Figure 1 were also in fact candidates from IRAS/ISO, where fainter excesses could be probed for various reasons, such as stellar proximity, or hotter photospheres or warmer dust than average.

3.3 Single population hypothesis

We first test the simplest possible hypothesis, that all Solar-type stars have debris discs drawn from a single distribution. A suitable function is sought that fits the excesses, plus information in the low net excess for systems that are not detected. The single-population hypothesis is unlikely to explain all systems completely, but provides a testable empirical approach.

Figure 1 shows (black line) a best fit to the debris detections with $E_{70} = 0.5$ to 17, given by

$$E_{70} = 0.09x^{-1.08} \quad (1)$$

where x is the star rank, and the correlation coefficient is 0.98. The single-population hypothesis is thus a rather good empirical fit to the systems detected, in spite of the wide range of stellar ages, spectral types, etc. The regime at $E_{70} < 0.5$ was excluded as a different dust behaviour is predicted (see below), and includes only 4 detected systems.

If the Equation 1 fit continued for all ranks up to 1, then the last star would have E_{70} of 0.09, and the mean in the undetected population at $x > 0.3$ would be 0.16. If this extrapolation applied, more detections should have been made, given a 3-sigma threshold of ~ 0.15 set by uncertainties ~ 0.05 in the photospheric levels as discussed above. Also, the true mean is unlikely to be so high, as among the 24 stars with the smallest excess-errors, there are only four objects with E_{70} measurementts even as high as ~ 0.25 (2.5σ upper limits ~ 0.4). This suggests a drop in dustiness among the majority population of stars.

3.4 Dust generation

The hypothesis above assumes one distribution for the amount of dust per star, but given some range of initial circumstellar disc properties, it is more likely that the quantity of comets per star forms the underlying distribution. In this case, the amount of dust generated needs to take

[3] The net value from all stars without debris detections is similar at -0.01 ± 0.02 but is more influenced by unphysical negative excesses, down to $E_{70} = -0.7$. These may indicate uncertainties in the photospheric models, with the two lowest values corresponding to stars at the extremes of the spectral type range, for example.

into account the dust removal processes, and as discussed by Dominik & Decin (2003), this depends on the number of colliding bodies. In massive discs, the dominant destructive mechanism is collisional and $N_{dust} \propto N_{comets}$, while in diffuse discs where the Poynting-Robertson (light drag) effect removes dust, $N_{dust} \propto N_{comets}^2$. This distinction between high- and low-mass discs, in the collisional and PR-drag dust removal regimes respectively, is also discussed by Meyer et al. (2007).

Wyatt (2005) has shown that the discs readily detectable in the far-infrared are in the high-mass regime, but to extrapolate here to the whole population of stars, the dust generated in the low-mass cases must also be calculated. This transition occurs where the fractional luminosity of the debris is

$$f_{crit} = L_{dust}/L_* = [2 \times 10^4 (r/dr)(r/M_*)^{1/2}]^{-1} \quad (2)$$

for disc radius and width r, dr in AU and stellar mass M_* in solar masses. It is obtained from the limit where PR-drag and collision lifetimes are equal, for grains where the radiative force is half the gravitational force (Wyatt 2005). Using 11 resolved images of debris discs around Sun-like stars observed in the optical and submillimetre (Wyatt 2008; Greaves et al. 2009), we calculated their values of f_{crit}. These lie in the range 1 to 10 $\times 10^{-6}$ with an average of 5×10^{-6}. The corresponding 70 μm ratio E_{crit} can then be calculated (Beichman et al. 2006), and for dust temperatures of 40-80 K and stellar effective temperature similar to the Sun, E_{crit} is on average 0.5 at 70 μm. Hence, if all Sun-like stars possess debris discs of similar scales to the resolved systems[4], then there should be a downturn in dustiness below $E_{70} \approx 0.5$, even if there is a single smooth distribution of number of comets per star.

The dotted line in Figure 1 shows this extrapolation beyond $E_{70} = 0.5$, assuming that the remaining systems are less dusty according to $E \propto N_{dust} \propto N_{comets}^2$ but continuing the same power-law distribution for $N_{comets}(x)$, i.e. of a form like Equation 1. In this case, the predicted mean E_{70} is reduced from 0.16 to 0.06, in better agreement with the estimate from the data of 0.03 ± 0.02 for all the stars at $x > 0.3$. Thus, the single-population hypothesis taking into account the different regimes of dust removal can match all the present observational results.

3.5 Comet populations

The number of comets per star can next be estimated from the dust excess, albeit via several scalings so the the final values are only approximate. To connect comets and excesses, we consider the τ Ceti debris disc, which is one of the nearby resolved examples and has $E_{60} = 0.75 \pm 0.15$ (Habing et al. 2001). These ISO observations were made with a slightly wider and shorter wavelength-centred filter than the 70 μm Spitzer/MIPS data, so we estimate a correction using stars detected by both ISO and Spitzer (Habing et al. 2001; Trilling et al. 2008). The dust signals are similar at 60 and 70 μm but the photosphere is fainter by a factor of 0.5±0.1 in the Spitzer data, from 6 G-dwarfs in common and with no debris. Hence, we adopt $E_{70} = 1.5$ for τ Ceti, while for the parameters of this system $E_{crit} \approx 0.85$, and so $E_{\tau \mathrm{Ceti}} \approx E_{crit} \times 1.8$. Since τ Ceti has an estimated 1.2 $M_\oplus$ of colliding bodies of radii $r \leqslant 25$ km (Greaves et al. 2004), under the assumption of a collisional cascade with incremental population $dN(r) \propto r^{-3.5}$, then E_{crit} would correspond to 0.7 $M_\oplus$. However, models (Löhne et al. 2008, e.g.) consider colliders up to $r = 75$ km, so including this extra contribution raises the critical mass to 1.3 $M_\oplus$. Thus, with the assumption that the dust in all systems comes from a collisional cascade fed by 75km objects, the general scaling is

$$E_{70}/0.5 = (M_{r \leqslant 75km}/1.3\ M_\oplus)^\alpha \quad (3)$$

where 0.5 is the generic value of E_{crit}, and α is 1 for $E > E_{crit}$ and 2 for sub-critical discs.

The mass in bodies of $r \leqslant 75$ km per star is then predicted to range from 60 down to 0.2 Earth masses, with the detected debris discs hosting $\gtrsim 1\ M_\oplus$ of comets. The shape of the population is the same as the excesses fitted in Figure 1, i.e. M_{comets} approximately inversely proportional to x, so the most massive belts are rare. The probability that a star's comets exceed a given mass is found by inverting the rank-mass expression to give

$$P(> M_{comets}) = 0.26/M_{comets}^{0.93}, \quad (4)$$

applicable to the mass in bodies with $r \leqslant 75$ km. The highest mass appears realistic, for example it is comparable to the 20-30 $M_\oplus$ of colliders inferred around the A-star Fomalhaut (Wyatt & Dent 2002), which hosts a bright debris disc with $E_{70} > 20$ (Stapelfeldt et al. 2004). The exact masses would be modified if the comets do not follow a collisional cascade – for example, Hahn & Mahotra (2005) fit the size-distribution for the Kuiper Belt as a double power-law with many small bodies but a depletion at sizes greater than 65 km. Adopting this distribution for the exo-comet belts would increase the fraction of the total mass that is in the collider population by a factor of about 2.5.

3.6 Models

Although the fit used here is simply empirical, analytical models for evolving debris disc populations in fact produce similar trends. The models of Wyatt et al. (2007) have been applied to FGK stars surrounded by a range of planetesimal discs. These discs have masses drawn from a log-normal function and sizes from a power-law distribution, as in the previous model for debris discs of A-type host stars (Wyatt et al. 2007). The model systems are sampled as if observed at random ages and then ranked as in Figure 1. The general behaviour of a steep decline from a few very dusty systems down to a long tail of low-debris stars is easily reproduced, adopting planetesimal populations of a few Earth masses and discs extending out to a few tens of AU. Kains et al. (in prep.) will present the final model parameters fitting both 70 and 24 μm debris statistics among the Spitzer-surveyed FGK stars.

[4] Only 3 of the 11 resolved systems are in our present sample, and there could be a bias to larger systems where the aim is to make resolved images, although the resolved examples were not chosen for observation on such a priori expectations.

4 THE SOLAR SYSTEM

4.1 Kuiper Belt properties

We now compare the 70 μm excess of the Kuiper Belt (if it were viewed from outside) to the extrasolar values. The Solar System's far-infrared dust flux is unfortunately not well established, although Landgraf et al. (2002) confirmed that Kuiper Belt dust does exist, via impacts onto the Pioneer spacecraft as they entered the outer Solar System. However the emission from this dust from an Earth viewpoint is a small perturbation to the much brighter Zodiacal flux. Aumann & Good (1990) used IRAS scans to estimate that the peak Kuiper Belt flux is 3×10^{-8} W m^{-2} sr^{-1} at 60 μm (in a 40 μm bandpass), and the main belt on the sky is effectively $\approx 10^{\circ}$ wide[5] (Morbidelli et al. 2003). Summing over this area and dividing by the bandpass to give a per-frequency-interval unit then gives a total flux of approximately 1 MJy ($\pm$0.5 MJy from the scatter in different scans). Subsequent COBE data with a similar 60 μm passband favour an upper limit at the lower end of this range (Backman et al. 1995). We assume that the 70 μm dust flux will be similar, while the Solar photospheric emission would be 100 MJy if seen at the approximately 45 AU distance of the Kuiper Belt[6].

The Sun's excess at 70 μm is therefore $\approx 0.01 \pm 0.005$ from IRAS, or possibly less from the COBE limit. These values of excess for the Kuiper Belt are remarkably small. Allowing a 2σ uncertainty so that E_{70} can be as high as 0.02 would imply that $x \geqslant 0.9$. Hence, the Sun is one of the *least dusty* systems (Figure 1), or possibly not a member of the single population being tested in our hypothesis.

The total mass in Kuiper Belt bodies has been estimated at a few hundredths of an Earth-mass, from deep surveys finding objects as small as 25 km diameter (Bernstein et al. 2004). The two-power-law model of Hahn & Mahotra (2005) can be used to estimate the total belt mass, adopting their generic albedo of 0.04. The Kuiper Belt would then sum to ~ 0.08 M$_{\oplus}$ in the $r \leqslant 75$ km regime (or somewhat smaller in a collisional cascade, or with more recently-adopted higher albedo). In contrast, in our single population hypothesis the lowest mass in colliders is ≈ 0.2 M$_{\oplus}$, and so the Kuiper Belt again appears to be an outlier, or at the extreme end of the range.

4.2 Detectability of Kuiper Belt analogues

An excess of order one per cent above the stellar photosphere will be very difficult to detect around nearby stars, even with the newly-launched Herschel mission. The PACS/70 chopping mode was predicted to detect ≈ 3 mJy sources with 5σ confidence in 1 hour, whereas the Sun if seen for example at 6 pc would have a photospheric signal of 135 mJy. Such an excess, at our Solar upper limit of 0.02, could thus in principle be robustly detected in an hour. In practice, there are only a dozen Sun-like stars within this distance, while beyond it a disc of Solar System dimensions would span less than three 5-arcsec telescope beams, and so uncertainties in subtracting the blended stellar signal would be re-introduced. However, Herschel will be able to explore somewhat larger excesses very efficiently. For example, if 5 % uncertainties in stellar models allow the detection of $E_{70} \approx 0.15$, Herschel is predicted to detect debris in 35 % of systems (according to the grey line extrapolation in Figure 1), compared to about 20 % of the stars observed with Spitzer.

5 IMPLICATIONS

The single population hypothesis discussed above fits both the debris systems detected by Spitzer and the net upper limit for the remaining stars, once the switch of dust removal to Poynting-Robertson drag is taken into account. If the Sun is a member of this hypothetical population, it must be one of the least dusty systems, within the last ten per cent. The estimates of mass in colliding comets suggest the Kuiper Belt population may actually be a depopulated outlier, with only a few-hundredths of an Earth-mass in colliding bodies up to tens of kilometre sizes. Roughly a third of similar stars are predicted to host an order of magnitude more comets; therefore, implications for impacts on any terrestrial planets need to be considered.

Since the Sun is a normal mid-main sequence G-dwarf, these results are surprising. Further, the primordial Kuiper Belt should have been much dustier and a bright member of the inferred single population. It is estimated that at least 10 M$_{\oplus}$ of rocky material was needed in order for the Kuiper Belt bodies to form (Morbidelli et al. 2003), and this total belt mass would place the young Sun around $x \sim 0.1$ in Figure 1. However, between the formation stage at ~ 0.1 Gyr and today, the Kuiper Belt should only have declined about four-fold in dust luminosity (Löhne et al. 2008), so its present-day rank would be $x \sim 0.3$, inconsistent with the observed rank of $x \gtrsim 0.9$.

The key to these results is the dispersal of many Kuiper Belt bodies, so that the population is now very depleted (Morbidelli et al. 2003, e.g.). The Nice model (Gomes et al. 2005) proposes that dispersal occurred when Jupiter and Saturn crossed their mutual 2:1 mean motion resonance as they migrated outwards; this event would have moved Uranus and Neptune onto enlarged eccentric orbits and consequently disrupted the comet belt. This model can explain ejection of many objects, and can be synchronized with the Late Heavy Bombardment of the Earth-Moon system at about 0.7 Gyr. However, the existence and timing of this event depend on the precise architecture of the system of gas giants (Thommes et al. 2008). Such as dispersal of around 99 % of the comet mass could readily shift the Solar System's excess to a low state and thus a high rank, as inferred here – a process recently modelled in detail by Booth et al. (2009). However, they find that < 12 % of Sun-like stars can have undergone such an event, as there is no global drop in dustiness at mature ages (Figure 2), so system clearing can not have been common. Gáspár et al. (2009) infer roughly

[5] We include only the classical belt and neglect dust that could be generated over a wider belt by collisions among scattered disc objects. Levison et al. (2008) suggest such an event created a recently discovered family of comets, but models are not well constrained by this one data point.

[6] This value based on the Sun's effective temperature was checked against a photospheric calculation for the MIPS/70 passband (Trilling et al. 2008) for the 'Solar twin' star HD 146233 (Soubiran & Triaud 2004).

similar proportions, based on the small number of stars that could be undergoing clearout events in the 760-Myr old cluster Praesepe. Thus in the present context, although comet-clearing by giant planets could shift the ranks of individual stars to much higher values, the data imply that such stars are only a small sub-set. This may be neglected in the single population hypothesis, as the net excess at $x > 0.3$ is presently poorly defined, and so switching a few per cent of planet-hosting stars to a low- or zero-dust state would have little effect on the net debris estimate.

5.1 Relation to giant planets

From long-term trends in Doppler wobble surveys, Cumming et al. (2008) estimate that $\approx$ 18 % of Sun-like stars host giant planets, of above about Saturn's mass and orbiting within 20 AU. Here we assume that any such planet orbiting within 3 AU would be disruptive, for example perturbing a terrestrial planet at $\sim$ 1 AU into an unstable or eccentric orbit, or in some migration scenarios preventing a habitable planet from forming (Fogg & Nelson 2009). Excluding this 8 % of systems leaves 10 % of stars hosting a gas giant at 3-20 AU, among which four out of every ten planets (generally above Jupiter's mass) are already discovered (Cumming et al. 2008). A small correction should be made for approximately 1 % of star systems found to host another lower-mass giant that is closer in, although this is less than the uncertainty of about 3 % in the extrapolation to orbits as distant as 20 AU. The result is that $\approx 9 \pm 3$ % of Sun-like stars should host gas giants no closer in than 3 AU, and are therefore reasonably analogous to the Solar System, with one-third of this population already discovered. Hypothesizing optimistically that all these stars could also have an unknown ice giant planet like Uranus or Neptune, the minimum conditions are met for gas giant interactions that could end with disruption of a comet belt outside the ice giant (should such a belt exist).

It is presently uncertain how giant planet systems and comet belts are related. Few stars have both gas giants and debris discs (Greaves et al. 2007; Moro-Martín et al. 2007), and systems with both phenomena have similar excesses to non-planet-hosts (Bryden et al. 2009). However, there could be a class of systems with many infalling comets and frequent impacts on any terrestrial planet(s). One archetype is HD 10647 which has a very high E_{70} of 50 and so an inferred $>$ 100 $M_\oplus$ of colliders; this object is $>$ 1 Gyr old (Liseau et al. 2008), while the four dusty planet-hosts of Figure 3 are about mid-main sequence. Consequently, it could be very difficult for complex life to ever evolve in these systems with at least twenty times more colliders than the Sun, if gas giants perturb these bodies into the inner regions. (Energetic impacts more frequently than every $\sim$ 10 Myr would probably hinder recovery of biodiversity (Krug & Patzkowsky 2004); however, creation of large heated impact basins could favour the appearance of simple thermophilic life (Abramov & Mojzsis 2009).) On the other hand, whether there is any connection between *faint* debris levels and gas giants is very difficult to determine. There are 14 planets hosts in our sample that do not have debris detections, and for these the mean E_{70} is 0.05 ± 0.05, not significantly different from 0.03 ± 0.02 estimated for null-debris stars in general.

5.2 Analogue exo-Earths

An analogue planet to our own is hypothesized to have a roughly similar impact rate. Impacts much faster than the rate experienced on Earth, of about one every 100 Myr for 10 km bodies, are likely to cause a serious extinction problem (e.g. halving the number of species after each event). However, a much slower impact rate could mean that life would stay at a very simple level, with no need to adapt to changes in environment. Here we consider a cometary population comparable to or lower than that of the Sun as similar, but also note that the slope of the inferred E_{70} is shallow at large x, so a considerable population could be only a few times dustier (depending on the poorly known Solar E_{70}). With this basic hypothesis, we then need to link impact rates to the configuration of the giant planets and comet belts. Unfortunately, this is computationally expensive to study for many systems (Horner & Jones 2008, e.g.). Modelling (Greaves, Jeffers, Horner et al., in prep.) will compare the Solar System, with rather few comets but several perturbing giant planets, to representative common extrasolar architectures, such as many more comets but fewer perturbing planets. In the interim, we can consider two cases at opposite extremes: one where debris and giant planets are unconnected phenomena, and one where gas giants beyond 3 AU are a hypothetical signpost to systems where comets are cleared out.

The results above then suggest that $\lesssim$ 10 % of stars have as few comets as the Sun (based on its E_{70} upper limit), while about 9 % of stars host an innermost gas giant beyond 3 AU. If these phenomena are uncorrelated, then the product of these rates implies that only up to $\sim$ 1 % of Sun-like star systems would be analogous to our own, in the sense of a small comet population concurrent with outer-system giant planets. In the alternative case where giant planets can help to enforce a low comet population, this fraction of stars rises to an upper limit of 9 %, assuming further-out ice giants are also present and so interactions can clear out the comet belt. This estimate of 1-9 % for an analogue system may be optimistic, if the exo-Earth impact rate is critically sensitive to the configuration of gas giants; for example, the clearing of the Kuiper Belt required Jupiter and Saturn to cross a particular resonance, in the model of Gomes et al. (2005). Further, there may not be an exo-Earth around all Sun-like stars, or not within the Habitable Zone where water can be liquid on the surface; see Raymond et al. (2007) for a model prediction that stars of $\gtrsim 0.8 M_\odot$ are the most suitable hosts. On the other hand, our estimate of only a few per cent of analogue systems is too pessimistic if in fact the single population hypothesis does not apply, and there are $\gg$ 10 % of Sun-like stars with little dust. This is not possible to test with the current data, but Herschel observations should soon be able to test whether many stars host little dust.

Adopting up to 9 % as the preliminary estimate of the frequency of analogue systems allows us to estimate the distance to the nearest counterpart. In conjunction with the space density of Sun-like hosts, which for mid-F to late-K dwarfs is 0.01 pc^{-3}, the nearest analogue system should lie within 13 pc. The nearest *presently* known analogue candidate (in the sense of planet and comet content) is the G8 star HD 154345 at 18 pc distance, which has no obvious Spitzer 70 μm excess and hosts a Jupiter-like planet at 4 AU. However, if only about one-third of the systems with gas giants beyond 3 AU have so far been discovered, a completeness correction suggests that a nearer analogue could lie within about 12 pc, or slightly closer given that not all nearby Sun-analogues as yet have published debris data.

6 CONCLUSIONS

Systems roughly analogous to our own, hosting a modest comet population and gas giants at a few AU or beyond, are inferred to be rather uncommon. If Sun-like stars often host terrestrial planets in the habitable zone, only a few per cent of these are likely to have a similar debris environment. A few systems may have catastrophic bombardment, even at mid-main sequence age, if gas giants perturb some of their numerous comets into the inner system. At the other extreme, the majority population should be stars without giant planets but with many comets, for which further modelling is needed to assess the rate of planetary impacts. The closest presently-known system that is roughly like our own lies at 18 pc, but another probably exists with around 10 pc given the completeness of debris and giant planet surveys so far. This result is encouraging for future facilities aiming to study habitable exo-Earths, such as DARWIN, TPF and ELT.

ACKNOWLEDGMENTS

We thank the referee for comments that helped to clarify several lines of argument. JSG thanks STFC and SUPA for support of this work.

REFERENCES

Abramov O., Mojzsis S.J., 2009, Nature 459, 419
Aumann H.H., Good J.C., 1990, ApJ 350, 408
Backman D.E., Dasgupta A., Stencel R.E., 1995, ApJ 450, L35
Beichman C.A. et al., 2006a, ApJ 652, 1674
Bernstein G.M., Trilling D.E., Allen R.L., Brown M.E., Holman M., Malhotra R., 2004, AJ 128, 1364
Booth M., Wyatt M.C., Morbidelli A., Moro-Martín A., Levison H.F., 2009, arXiv:0906.3755
Bryden G. et al., 2009, ApJ 705, 1226
Bryden G. et al., 2006, ApJ 636, 1098
Carpenter J.M. et al., 2009, ApJS 181, 197
Cumming A., Butler R.P., Marcy G.W., Vogt S.S., Wright J.T., Fischer D.A., 2008, PASP 120, 531
Decin G., Dominik C., Malfait K., Mayor M., Waelkens C., 2000, A&A 357, 533
Dominik C., Decin G., 2003, ApJ 598, 626
Fogg M.J., Nelson R.P., 2009, A&A 498, 575
Gáspár A. et al., 2009, ApJ 697, 1578
Gomes R., Levison H.F., Tsiganis K., Morbidelli A., Nature 435, 466
Greaves J.S., Wyatt M.C., Bryden G., 2009, MNRAS 397, 757
Greaves J.S., Fischer D.A., Wyatt M.C., Beichman C.A., Bryden G., 2007, MNRAS 378, L1
Greaves J. S., Wyatt M. C., Holland W. S., Dent W. R. F., 2004, MNRAS 351, L54
Greaves J.S., Wyatt M.C., 2003, MNRAS 345, 1212
Habing H.J. et al., 2001, A&A 365, 545
Hahn J.M., Malhotra R., 2005, AJ 130, 2392
Hillenbrand L.A. et al., 2008, ApJ 677, 630
Horner J., Jones B.W., 2008, A&G 49, 1.22
Jeffers S.V., Manley S.P., Bailey M.E., Asher D.J., 2001, MNRAS 327, 126
Kim S. et al., 2007, BAAS 39, 814
Krug A.Z., Patzkowsky M.E., 2007, Paleobiology 33, 435
Landgraf M., Liou J-C., Zook H.A., Grün E., 2002, AJ, 123, 2857
Levison H.F. Morbidelli A., Vokrouhlický D.D., Bottke W.F. 2008, AJ 136, 1079
Liseau R. et al., 2008, A&A 480, L47
Löhne T., Krivov A.V., Rodmann J., 2008, ApJ 673, 1123
Meyer M.R. et al., 2008, ApJ 674, L181
Meyer M.R., Backman D.E., Weinberger A.J., Wyatt M.C., 2007, in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil (eds.), University of Arizona Press, Tucson, p.573
Morbidelli A., Brown M.E., Levison H.F., 2003, Earth, Moon & Planets, 92, 1
Moro-Martín A. et al. 2007, ApJ 658, 1312
Raymond S.N., Scalo J., Meadows V.S., 2007, ApJ 669, 606
Soubiran C., Triaud A., 2004, A&A 418, 1089
Stapelfeldt K.R. et al., 2004, ApJS 154, 458
Su K.Y.L. et al., 2006, ApJ 653, 675
Thommes E.W., Bryden G., Wu Y., Rasio F.A., 2008, ApJ 675, 1538
Trilling D.E., Beichman C.A., Bryden G., Rieke G.H., Su K.Y.L., 2008, ApJ 674, 1086
Trilling D.E. et al., 2007, ApJ 658, 1289
Wyatt M.C., 2008, ARAA 46, 339
Wyatt M.C., 2005, A& 433, 1007
Wyatt M.C., Smith R., Su K.Y.L., Rieke, G.H., Greaves J.S., Beichman C.A., Bryden G., 2007, ApJ 663, 365
Wyatt M.C., Dent W.R.F., 2002, MNRAS 334, 589
Zahnle K., Arndt N., Cockell C., Halliday A., Nisbet E., Selsis F, Sleep N.H., 2007, Space Science Reviews 129, 35

This paper has been typeset from a TEX/ LATEX file prepared by the author.