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Predicting the incidence of planet and debris discs as a function of stellar mass

J. S. Greaves★

SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS

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ABSTRACT

The mass of solids in a young circumstellar disc may be the key factor in its efficiency in building planetesimals and planetary cores, and dust observed around young T Tauri and Herbig Ae stars can be used as a proxy for this initial solid content. The dust-mass distributions are taken from recent millimetre-wavelength data and fitted using survival analysis to take into account upper limits, and threshold disc masses for building planets and belts of comets are estimated. Amongst A stars, 20 per cent gas giant and 55 per cent debris disc systems are predicted, in good agreement with observations. For M stars, the predicted and observed planet frequencies agree at ∼2–3 per cent, and this low incidence is explained by a lack of massive discs. However, debris is predicted around ≈14 per cent of M stars, while only ∼2 per cent such systems have so far been found. This suggests that deeper searches such as with *Herschel* and SCUBA-2 may find a cold disc population previously missed around these low-luminosity stars. Also, an estimate of the efficiency of building millimetre-detected dust into planetary cores suggests that about one-third of M stars could host an Earth-mass planet – but as the dust is spread over large disc areas, such planets may orbit far from the star.

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

1 INTRODUCTION

The incidence of extrasolar planets is known to be a function of both stellar mass and metallicity. If the present-day metallicity of the star reflects that of its circumstellar material at early times, then metal-rich discs would be expected to build planetary cores more readily by grain coagulation. The stellar mass may enter if more massive stars have higher mass discs, as well as in factors such as shorter dynamical times for grains to collide. In the simplest approach, the mass of solids in a disc, i.e. the total mass M multiplied by the solid fraction Z, may be the relevant threshold for a successful outcome in forming planets or planetesimals (Greaves et al. 2007; Wyatt, Clarke & Greaves 2007). These two quantities M and Z can be readily estimated using proxies. Millimetre-wavelength emission from dust is rather optically thin (Andrews & Williams 2007b) and the derived disc masses in present-day star formation regions are canonically multiplied by a factor of ≈100 to include the gas content inherited from the interstellar medium. These masses are proxies in the sense that material already converted into larger bodies (from boulders up to planets) has little emitting area, and so potentially only some of the orbiting material is represented. A good proxy for the refractory proportion of material in discs of non-solar metallicity is the logarithmic [Fe/H] of the host star.

Greaves et al. (2007) showed that such a simple empirical model can reproduce the properties of both planets and debris discs around Sun-like stars. The presence of debris indicates collisions between planetesimals, such as icy outer system comets, treated in the model as a less successful mode of planet formation ending only in small bodies. Both the frequencies and metallicity dependencies of these two outcomes were well matched. In particular, forming planets requires a high solid mass to build the core, and so high metal fractions are advantageous, explaining the strong metallicity trend in the host stars (Wyatt et al. 2007). On the other hand, forming comet belts requires only modest amounts of material, and many discs meet this threshold regardless of metallicity, so it enters only weakly (Greaves et al. 2007). More complex approaches such as the simulations of Johansen, Youdin & Mac Low (2009) have confirmed that the outcomes of planetesimal formation should depend strongly on metallicity. Raymond, Scalo & Meadows (2007) have used a model of disc masses in solids to investigate the formation of terrestrial planets, finding in particular that habitable examples could be less likely for low-mass stars if they had insubstantial discs. A recent summary of our understanding of planetesimal growth is presented by Chiang & Youdin (2010).

Here our empirical model is expanded to test the planet and debris frequency expected for stars of higher and lower mass, namely A and M dwarfs. Their planetary systems are now being discovered by radial velocity surveys (of subgiant descendents in the case of A stars), and their debris discs seen as far-infrared excesses, e.g. by

★E-mail: jsg5@st-andrews.ac.uk

the *Spitzer* satellite (Su et al. 2006; Gautier et al. 2007). Here the M, Z distributions are assessed, and while the [Fe/H] ranges among the stars are all similar, the disc-mass distributions differ markedly, leading to strong changes in incidence with stellar mass.

2 DATA

Metallicity data were first compared for different stellar types. Subgiants that are the descendents of A stars of $\approx$1.2–2.5 solar masses can be identified by absolute magnitude M_V of 0.5–3.5 and $B - V$ of 0.55–1.0 (Johnson et al. 2006), or similarly effective temperature of 5000–6300 K (Flower 1996). The Spectroscopic Properties of Cool Stars (SPOCS) study of nearby stars (Valenti & Fischer 2005) yields approximately 100 such subgiants with [Fe/H] measurements. A (log)normal fit to these values indicates mean and standard deviation μ, σ of $+$ 0.02, 0.23. This is very similar to values for nearby Sun-like dwarfs, with μ, σ of $-$0.01, 0.29 in the data of Valenti & Fischer (2005). For M stars, the derivation of metallicities based on photometry has recently been recomputed by Johnson et al. (2009). Using data they present for M stars within 20 pc, and their relation for [Fe/H] derived from K-magnitude height above the main sequence, μ, σ are found to be $-$0.06, 0.24. These distributions[1] are so similar that they cannot significantly affect planet-building potential around different classes of star.

The disc-mass distributions were then constructed and found to be quite different for A versus FGK and M stars (Fig. 1). The masses for the A stars are from Natta et al. (2004) in a millimetre-based compilation for young Herbig Ae objects.[2] Their plot of $M_{\rm disc}/M_{\rm star}$ versus $M_{\rm star}$ was used to derive $M_{\rm disc}$ for $M_{\rm star}$ of 1.2–2.5 solar masses. Since 11/45 of the disc-mass measurements were upper limits, a survival analysis was used to find the underlying distribution, implemented with the ASURV package (Lavalley et al. 1992). The resulting disc-mass distribution appears rather lognormal in form, and is centred at a mean of 25 Jupiter masses of gas and dust. For comparison, this is just above the Minimum Mass Solar Nebula of $\approx$20 Jupiter masses (Davis 2005) needed to supply the cores of all the Sun's planets. For FGK and M stars,[3] the millimetre surveys of Tau/Aur and Oph by Andrews & Williams (2005, 2007a) were used, comprising similar-aged stars to the HAe objects of Natta et al. (2004). Since these authors used a conversion of flux to dust mass yielding values a factor of 3 lower than in Natta et al. (2004), the masses have been shifted upwards by one bin ($\delta \log - M = 0.5$) in Fig. 1. The difference arises from using an opacity at 1-mm wavelength of 0.03 cm^2 g^{-1} rather than the 0.01 cm^2 g^{-1} found in the detailed grain model of Natta et al. (2004), which also agrees with recent literature values (Draine 2006). Survival analysis was again used to construct the base disc-mass populations for FGK and M stars, but more of the points are now upper limits, as the discs are less massive than for the HAe stars. There were 57 limits out of 111 measurements for the FGK dwarfs, and 57/106 for the M stars.

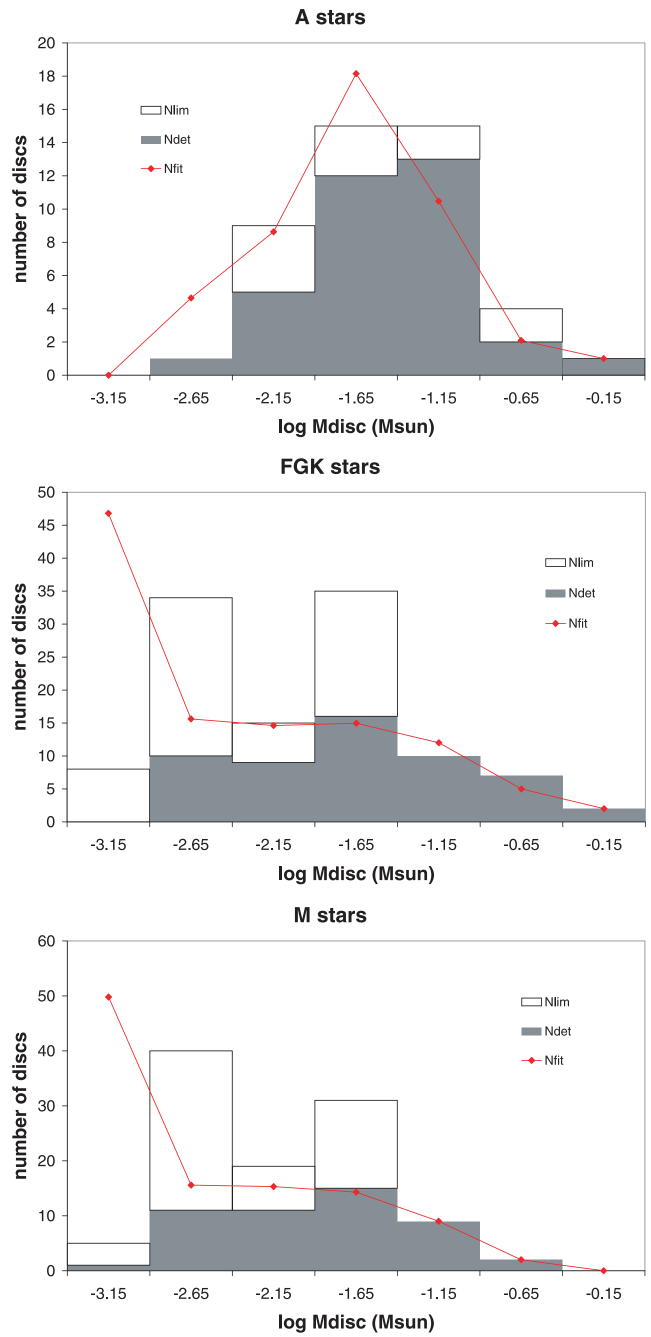

Figure 1. Distribution of disc masses (in gas plus dust) for A, FGK and M stars. Disc detections and upper limits are shown by filled and unfilled bars, respectively; the red lines show the fitted population from survival analysis (see text). X-axis labels are for the bin-centres. For reference, a solar mass is just over 1000 Jupiter masses; the lowest bin comprises discs of $<1.3 M_{\rm Jupiter}$ or $<4 M_{\rm Earth}$ in solids at solar metallicity.

The means are 4 and 3 Jupiter masses, respectively. There is also a large tail of insubstantial discs in both cases, which, combined with the lower means, suggests that these discs will have much less planet-forming capability than those of A stars. The low-mass tails include many Class III T Tauri stars, which may lose their discs early on (Luhman et al. 2010). All this disc-mass distributions are very broad, whereas the metallicity distributions would cover only about one bin on the scales of Fig. 1.

[1] Schlaufman & Laughlin (2010) argue that the mean [Fe/H] for FGK and M stars are about 0.1 dex lower than found here; such small shifts have negligible effect on the $M_{\rm solids}$ distribution.
[2] The data presented by Alonso-Albi et al. (2009) give a similar mass distribution but with fewer HAe stars.
[3] Pre-main-sequence M stars have rather vertical Hayashi tracks with modest change in effective temperature, so young and old objects of M type will have similar stellar masses. Other pre-main-sequence stars evolve towards hotter spectral types, but since most of the observed T Tauri objects have K classifications, they will still be within roughly 'Sun-like' classes at later times.

3 RESULTS AND PREDICTIONS

3.1 Planets

Since the metallicity distributions are all narrow and similar, the differences in $M_{\rm disc}$ should be the dominant factor, and the relevant thresholds for planet formation are now estimated. Greaves et al. (2007) argued that if a minimum solid mass is needed to grow a planetary core, then there will be observed examples of giant planets arising from a range of discs with this same solid mass, but ranging between massive/low-metal and lower mass/high-metal systems. The lowest metal system observed with a planet arises when the solids criterion was met only because the disc was at the extreme high end of total mass. The solid mass can then be expressed using the proxy data as

$$M_{\rm solids}^{\rm min} = M_{\rm disc}^{\rm max} 10^{[{\rm Fe/H}]_{\rm min}}/100. \quad (1)$$

The resulting parameters for all the spectral types are listed in Table 1. The input data on the disc masses are from the references in the previous section, and the metallicities of planet hosts are from http://exoplanet.eu/. The subsequent columns list the disc-mass thresholds needed to form planets and the predicted and observed frequencies. For FGK stars, the predicted incidence of around 8 per cent is in excellent agreement with the 8.5 per cent found in the systematic planet sample of Johnson et al. (2010). For A stars the planet agreement is also very good, with around 20 per cent both predicted and observed. For M stars, the incidence is 2–3 per cent, and the model correctly predicts a low value because few of the discs are massive (Fig. 1).

The solid-mass thresholds needed for forming giant planets are here found to be 200, 400 and 650$M_\oplus$ for A, FGK and M spectral types, respectively (Table 1). This trend qualitatively matches the expectation that grains will coagulate more readily in discs around more massive stars, as the dynamical (orbital) times are shorter.

Subsets of different types of planetary systems are not considered in detail here. Rocky 'super-Earth' planets form a small part of the FGK-hosted population (e.g. $\lesssim$10 $M_\oplus$ bodies contribute around 0.5 per cent incidence), and the requirements for building such bodies are considered briefly below. Also, there are likely to be systems with more gas giants orbiting further out – for example, Gould et al. (2010) estimate ~1/6 for the frequency of two-giant systems, from microlensing results – but these are not included here. The analysis is however self-consistent in using the lowest metal radial velocity detection to predict the planet frequency in this type of survey.

3.2 Debris discs

For the less successful outcome of building planetesimals, the threshold cannot be straightforwardly derived. Greaves et al. (2007) used the metallicity range of FGK debris hosts to estimate the mass threshold for building comet belts, but there is little similar data for A and M stars. Hence the simplest procedure is to infer the threshold from the data. In deep *Spitzer* surveys, approximately 19 per cent of FGK stars have debris discs detected at 70 μm (Greaves & Wyatt 2010), associated with belts of colliding planetesimals. Associating this outcome with discs of lower mass than those that build planets, this next 19 per cent of the $M_{\rm disc}$ distribution corresponds to >50 Earth masses in solids or >15 Jupiter masses in total at solar metallicity. This is eight times lower than the value needed for building planets. Making the minimal assumption that the efficiency of the planetesimal-building process is similar in all systems, a similarly reduced value can be applied for the other stellar masses. Discs of at least 25 and 80 Earth masses in solids would then be needed for A and M stars, respectively, to have debris.

The model results (Table 1) show a predicted debris incidence for A stars that is slightly low, but only at the -1σ bound (error on observed − predicted of 15 per cent in quadrature). For M stars, there is however an interesting discrepancy between the debris prediction of around 14 per cent and the observed incidence of as little as 2 per cent (Table 1). A few other M host debris discs have been discovered, but all around stars much younger than typical main-sequence lifetimes (Liu et al. 2004; Forbrich et al. 2008; Plavchan et al. 2009). It is possible that these M discs evolve down to lower dustiness than seen among A or FGK stars (Fig. 2), but given that FGK and M discs are similar at the T Tauri phase, an alternative explanation is favoured. As M dwarfs are of low luminosity, dust particles in thermal equilibrium with the star will be cool, compared to a grain on the same orbit around AFGK stars. In this case, the discs will have faint emission shifted to long wavelengths, and this introduces a survey bias (e.g. Matthews et al. 2007). There may be negligible excess above the M star photospheres at 70 μm, and exploratory millimetre surveys may not yet have reached deep enough to detect the discs.

There are some systems known with both gas giants and debris discs, but the statistics suggest the two phenomena are not correlated (Bryden et al. 2009); here in fact it is assumed that they are separate outcomes. In the uncorrelated case for FGK stars, a proportion of 0.08 (planet frequency) × 0.19 (debris frequency) or 1.5 per cent of stars would have planets and dust, so this should be a negligible population. A small number of planets around A hosts of debris discs has also been found in direct imaging surveys. These cases

Table 1. Predicted and observed percentages of giant planet and debris discs. The planet data are from the uniform-detectability sample of Johnson et al. (2010) and debris frequencies are from *Spitzer* 70-μm surveys (Beichman et al. 2006; Su et al. 2006; Gautier et al. 2007; Trilling et al. 2008), limited to data with signal-to-noise ratio >3. The debris frequency observed for FGK stars is used to make the predictions for other spectral types. The upper limit for M stars is from <1/15 objects detected by *Spitzer* at 70 μm in ≥3σ data (Gautier et al. 2007), while the bracketed value is from 1/50 detections in the millimetre survey of Lestrade et al. (2006, 2009). Poisson errors are based on the number of planet and debris systems detected, and the number of discs falling within the input mass bounds (see text). The parameters of equation (1) are listed in the four columns after the spectral types. The A star mass marked with a * symbol is actually the second most massive value from Natta et al. (2004), as another disc with large distance and uncertain mass was removed. The sample of Alonso-Albi et al. (2009) gives a comparable highest mass of 225 Jupiter masses among HAe stars within about 500 pc.

Spectral type	Max $M_{\rm disc}$ ($M_{\rm Jup}$)	Min [Fe/H] (planet)	Min $M_{\rm solids}$ ($M_\oplus$, for planet)	Min $M_{\rm disc}$ ($M_{\rm Jup}$, at [Fe/H] = 0)	f(planet) per cent		f(debris) per cent	
					Predicted	Observed	Predicted	Observed
FGK	600	−0.7	400	120	8 ± 3	8.5 ± 1.0	–	19 ± 3
A	150*	−0.36	200	60	20 ± 7	20 ± 3	55 ± 11	70 ± 11
M	270	−0.12	650	200	1.9 ± 1.3	3.3 ± 1.5	14 ± 4	<7 (~2)

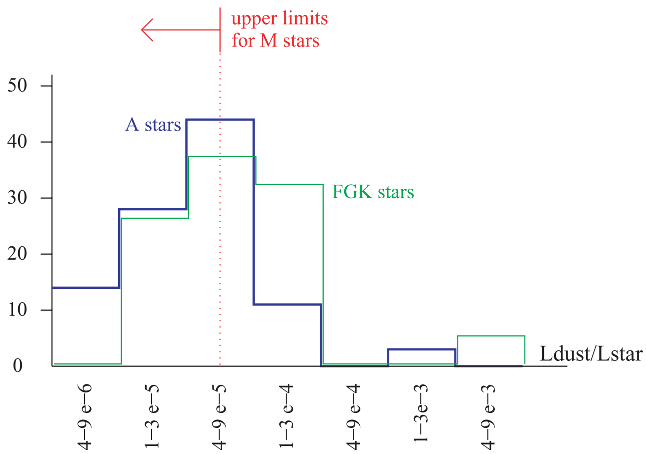

Figure 2. Distributions of percentage of stars versus fractional dust luminosities for A and FGK systems with debris detected at 24, 70 μm (Beichman et al. 2006; Su et al. 2006; Trilling et al. 2008). The typical upper limit for the M stars observed by Gautier et al. (2007) is shown at the top, and applies for dust at temperatures of ≈40–100 K.

are not considered as a separate class here. The stability of debris discs over several Gyr, in terms of size and mass and largest bodies present, has been studied in detail by Heng & Tremaine (2010).

3.3 Planet-building efficiency

The planetary systems of M dwarfs are of particular interest because these stars are so abundant in the Galaxy. The large solid threshold inferred for M stars to form planets (Table 1) suggests the core accretion process may be inefficient. A rough efficiency estimate can be made, assuming the solid content in the giant planets in the M star sample of Johnson et al. (2010) is of the order of 20 $M_{\rm Earth}$. For example, these planets are of $\gtrsim M_{\rm Saturn}$ and this is about Saturn's solid content (Saumon & Guillot 2004). A lower mass 'super-Earth' population is also being discovered of which the most massive observed in transit has a $20M_{\rm Earth}$ core plus ≈10–15 per cent atmospheric mass (Bean et al. 2008). If 20 Earth masses is a rough boundary above which planets got on to become gas giants, then we could equate this outcome at ∼3.3 per cent frequency with the same fraction of top-end discs, which have $\gtrsim$300 $M_\oplus$ of dust. In this case, the efficiency of incorporating disc solids (or at least the millimetre-detected component) is ∼20/300 or 7 per cent.

One consequence is that to build an Earth-mass planet, 15 $M_\oplus$ of dust in the disc would be needed. This occurs for around one-third of M stars (Fig. 1), so they are not all expected to form Earth analogues. Given that about three-fourth of main-sequence stars are of M-type, at least a quarter of nearby stars could host an Earth-mass planet under this simple scaling approach. However, the disc material spreads far from the star (Andrews & Williams 2007a), so these planets may only be able to form in large orbits, particularly as the Hill radius for accretion increases with radial distance. Microlensing is particularly well suited to the discovery of M dwarf systems hosting such low-mass planets in orbits out to around 10 au (Gould et al. 2010).

It is beyond the scope of this study to assess how many planets might migrate inwards, to the habitable zone around 0.1 au where temperatures are suitable for liquid water on the surface. Raymond et al. (2007) have simulated the formation of terrestrial planets, and found that habitable planets of $\gtrsim 0.3 M_\oplus$ (the boundary for plate tectonics and atmospheric retention) are much less likely for M dwarfs than G/K stars. Fig. 1 also suggests that discs substantial enough to form an Earth-mass planet are much more common around A stars, although these discs may also form giants, with implications for the supply of material and stability for terrestrial bodies (e.g. Fogg & Nelson 2009).

4 CONCLUSIONS

The disc-mass distributions for young A and M stars have been constructed and compared to those for Sun-like stars. Inferring the mass thresholds for forming extrasolar planet and debris discs, the higher incidence of both phenomena among A stars or their descendents is well reproduced, as is the low incidence of giant planets around M stars, which rarely have substantial discs. However, only about 2 per cent of nearby M stars have debris discovered so far, and several times more are expected. There may be a population of cool debris discs around red dwarfs largely missed in surveys so far. The new SCUBA-2 camera (Holland et al. 2006) observing at 450 and 850 μm will be ideally matched to cold dust, as is the highly sensitive *Herschel* satellite (Pilbratt et al. 2010), now observing out to 500 μm. A further prediction of the empirical calculations is that about one- third of M stars have the capability to form a 1 Earth-mass planet – however, such planets are likely to form far from the star, as the disc material is very spread out.

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