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Metallicity, debris discs and planets

J. S. Greaves,[1]★ D. A. Fischer [2]★ and M. C. Wyatt[3]★

[1]School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS
[2]Department of Astronomy, University of California at Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA
[3]UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

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ABSTRACT

We investigate the populations of main-sequence stars within 25 pc that have debris discs and/or giant planets detected by Doppler shift. The metallicity distribution of the debris sample is a very close match to that of stars in general, but differs with >99 per cent confidence from the giant planet sample, which favours stars of above average metallicity. This result is not due to differences in age of the two samples. The formation of debris-generating planetesimals at tens of au thus appears independent of the metal fraction of the primordial disc, in contrast to the growth and migration history of giant planets within a few au. The data generally fit a core accumulation model, with outer planetesimals forming eventually even from a disc low in solids, while inner planets require fast core growth for gas to still be present to make an atmosphere.

Key words: circumstellar matter – planetary systems: formation – planetary systems: protoplanetary discs.

1 INTRODUCTION

Around 150 extrasolar planets have now been detected by the radial-velocity (Doppler shift) method, in which precision spectroscopy reveals the reflex motion of the star. All of these detections are of giant planets, and the majority of those found so far have small orbits (three-quarters within 2 au); consequently, these systems are quite unlike the Solar system. It has recently been shown that stars with higher metallicity, for example, measured by the iron abundance [Fe/H], are more likely to have radial-velocity detections. The metallicity distribution of the stars with planets peaks at a more positive value than for nearby stars in general, and the occurrence of gas giant planets rises from a few per cent at solar metallicity to more than 20 per cent for stars with twice the metal content of the Sun (Fischer & Valenti 2005; Santos et al. 2005). This trend could be either because a higher mass of refractory elements promotes planet formation (perhaps speeding up growth of a solid core), or because planets that migrate inwards and fall on to the star then boost its surface metallicity. The latter theory is now seen as unlikely (Fischer, Valenti & Marcy 2005), as stars with deeper convection zones should dilute out this metal-enriched layer, and this trend is not seen.

As well as planets, the primordial stellar disc should produce a cometary zone like the Kuiper Belt around the Sun. This consists of planetesimals of ∼1–1000 km in size, that grew slowly in large orbits at tens of au and so did not accumulate into planet-mass bodies. It is collision between such planetesimals which is thought to generate dust that is seen in thermal emission in the far-infrared (FIR) by *IRAS* and the *Infrared Space Observatory* (*ISO*). The relation of these small bodies to inner planets is uncertain: Greaves et al. (2004a) found little overlap in the debris and Doppler populations among nearby Sun-like stars, but Beichmann et al. (2005) show from deeper thermal searches that ∼25 per cent of stars with inner planets have debris, compared to ∼10 per cent of similar stars without planets. Here we search for any relation of the stellar metallicity (presumed to be shared with the primordial disc) and the occurrence of debris discs. Some comparisons are made with models for the formation and migration of giant planets.

2 DATA

We use results from the spectral-synthesis modelling program of Valenti & Fischer (2005), who measured metallicity [M/H] for 1040 stars on the Lick, Keck and Anglo-Australian Telescope (AAT) planet-search programmes. These planet-search surveys generally exclude chromospherically active stars and binaries with angular separations less than 2 arcsec. The measurements are from a combination of lines of Fe, Si, Na, Ti and Ni, and are accurate to 0.025 dex (1σ) in [M/H]; all values are logarithmic with respect to solar.

The debris-disc survey uses literature results[1] of stars which exhibit excess thermal emission and so are thought to host a debris disc. Our present study is limited to the volume within 25-pc distance of

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★E-mail: jsg5@st-and.ac.uk (JSG); fischer@astro.berkeley.edu (DAF); wyatt@roe.ac.uk (MCW)

[1] These are summarized in our searchable data base at http://www.roe.ac.uk/ukatc/research/topics/dust/identification.html.

Table 1. Stars with radial-velocity planets and *IRAS*/*ISO* debris excess. Only HD 22049 (ϵ Eridani, italicized) is in both lists. The metallicity values [M/H] are from Valenti & Fischer (2005) and the spectral types are from http://stellar.phys.appstate.edu/ or SIMBAD. The stars are listed by increasing [M/H] for ease of comparison.

Planet stars	[M/H]	Debris stars	[M/H]
HD 13445 (K1V)	−0.20	HD 10700 (G8V)	−0.36
HD 143761 (G0V)	−0.14	HD 196378 (F7V)	−0.32
HD 192263 (K2V)	−0.07	HD 20794 (G8V)	−0.23
HD 117176 (G5V)	−0.01	HD 20807 (G2V)	−0.23
HD 22049 (K2V)	0.00	HD 1581 (G0V)	−0.18
HD 128311 (K3V)	+0.01	HD 32923 (G1V)	−0.13
HD 95128 (G1V)	+0.02	HD 10647 (F8V)	−0.08
HD 186427 (G3V)	+0.02	HD 69830 (K0V)	−0.08
HD 39091 (G0V)	+0.04	HD 207129 (G0V)	−0.04
HD 147513 (G1V)	+0.07	HD 22484 (F8V)	−0.03
HD 17051 (F9V)	+0.09	HD 30495 (G3V)	−0.01
HD 114783 (K1V)	+0.10	HD 221354 (K0V)	−0.01
HD 9826 (F8V)	+0.12	HD 67199 (K1V)	−0.00
HD 217014 (G3V)	+0.15	*HD 22049* (K2V)	0.00
HD 3651 (K0V)	+0.16	HD 214953 (G0V)	+0.03
HD 19994 (F8.5V)	+0.17	HD 48682 (F9V)	+0.09
HD 75732 (K0IV–V)	+0.25	HD 17925 (K1V)	+0.11
HD 120136 (F7IV–V)	+0.25	HD 1835 (G3V)	+0.22
HD 160691 (G3V)	+0.26		
HD 145675 (K0IV–V)	+0.41		

the Sun, as in Greaves et al. (2004a), because this region is fairly complete in *IRAS* and *ISO* detections of moderate FIR dust excesses around Sun-like stars. For example, for G-type dwarf stars, Greaves & Wyatt (2003) find a detection rate of 7 per cent, extrapolated up to 12 per cent based on completeness arguments. [Four more G-star discs within this volume have recently been added by deeper observations (Beichmann et al. 2005; Bryden et al. 2005), increasing the rate to 9 per cent.] Here we limit the objects to be included to spectral classes between F7 and K3 and luminosity class V or IV–V. This eliminates giants that may make dust in their envelopes, stars of type too early to have suitable lines for spectroscopy, and late types for which there are very few dust detections.

For this search volume, there are 310 stars with [M/H] values measured by Valenti & Fischer (2005),[2] and among these there are 20 systems with radial-velocity planets and 18 debris systems (Table 1). Only ϵ Eridani has both a planet and debris (Greaves et al. 1998; Hatzes et al. 2000). A few extra systems within 25 pc are omitted, including four discs (two with associated planets) recently discovered by *Spitzer* (Beichmann et al. 2005; Bryden et al. 2005), and some disc candidates from a re-analysis of *IRAS* data by Saffe & Gómez (2004). This latter study is based on weak *IRAS* excesses, and four of the six systems identified with *IRAS* at 25 μm do not have 24-μm excesses on re-examination by *Spitzer* (Beichmann et al. 2005). The entries included in Table 1 are mostly thought to be robust, with the possible exceptions of HD 32923 and HD 67199, classified by Oudmaijer et al. (1992) and Mannings & Barlow (1998) as excesses but at a level of only $\approx 1.5\sigma$.

3 METALLICITY DISTRIBUTIONS

Fig. 1 compares the [M/H] distributions of the stars with debris, those with inner planets, and among the 310 Valenti & Fischer (2005) stars in general. The plots of cumulative fraction of objects versus metallicity demonstrate a clear division amongst the populations. Stars with debris match very closely on to the base population of all the stars, while the radial-velocity detections are distributed amongst stars richer in metals. A Kolmogorov–Smirnov test shows a probability of only $P = 0.6$ per cent that the debris and planet stars have the same metallicity distribution. Although each data set has only 18–20 stars, these distributions are likely to be robust; for example, for the planet hosts, the proportions by metallicity bin differ negligibly from those in a three-times larger sample plotted by Fischer et al. (2005).

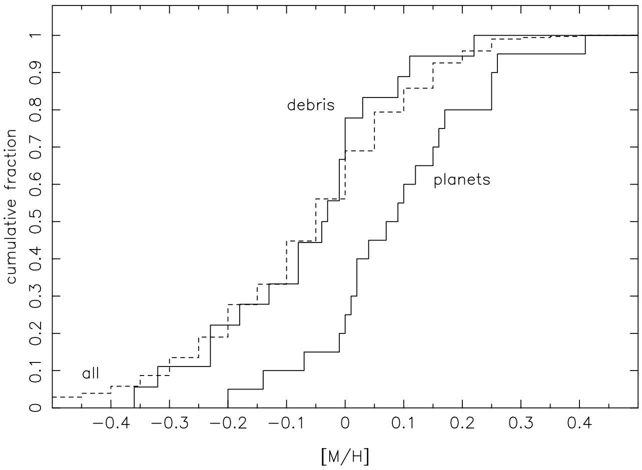

Figure 1. Cumulative distributions for the 25-pc sample, for all the stars (dashed line, in bins of 0.05 in metallicity) and the sub-samples with debris detections and radial-velocity planets.

A difference is also seen in detection rate versus [M/H]. We group the full population of stars into two metallicity bins: $-0.5 <$ [M/H] < 0.0 and $0.0 \leqslant$ [M/H] $< +0.5$ (this excludes only four out of the 310 stars having metallicity below -0.5; none of these has a planet or debris disc). The rate of giant planet occurrence in these two bins is 2 ± 1 and 11 ± 3 per cent, respectively. However, debris discs are detected at a rate of 7 ± 2 and 4 ± 2 per cent, respectively, in these two metallicity bins.[3] Errors are estimated from Poisson statistics, from which we find that the two rates differ in the planet group but not in the debris group. This confirms that planets are more likely to be found among metal-rich stars, but debris discs do not favour higher metallicity. The distribution among debris discs in fact tracks the metallicity distribution of all stars, with or without detected planets.

3.1 Bias effects

In this range of metallicity, Fischer & Valenti (2005) show that there is no bias against the detection of extrasolar planets among the metal-poor stars. Although metal-poor stars have fewer and shallower lines, this does not impact Doppler precision until [Fe/H] drops below -1.0 (a negligible fraction of nearby stars). For debris, the FIR flux may be enhanced for an Fe-rich composition, comparing extreme cases of minerals with and without iron (Wolf & Hillenbrand 2003). This enhanced detectability should affect only the highest-metallicity stars, and for example, only 1 per cent of our

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[2] A few are classification IV sub-giants, but this is unlikely to affect the overall metallicity distribution.

[3] HD 22049 is excluded from the rates, as it has both a disc and a planet detection.

stars are more than twice as metal-rich as the Sun. With such small number statistics, we do not expect, nor do we see, an increase in the fraction of debris discs around metal-rich stars.

The metallicity divergence of Fig. 1 could in principle be produced by an age bias. The Galactic metal fraction has increased with time as nucleosynthesis proceeds through more generations of stars, so the expected trend is towards higher metals for younger stars (with considerable scatter due to different birth environments spread throughout the Galaxy). Hence, the debris stars could be biased towards lower metal content simply if drawn from an older population. However, both of the sub-samples are found to include similar age ranges of stars. Our isochrones (Valenti & Fischer 2005) give a median age of 5 Gyr for both the planet host stars and for the debris systems. Wright et al. (2004) list ages based on chromospheric activity for about half of our stars, and the median values are similar at 6 and 4 Gyr for the planet and debris systems, respectively. There is thus no evidence that the debris hosts are preferentially old. This agrees with recent studies finding debris around stars of all main-sequence ages (Greaves et al. 2004a,b; Beichmann et al. 2005), with if anything a small bias towards younger average age if debris is more prevalent in the first few 100 Myr of stellar lifetimes (Habing et al. 2001).

4 DISCUSSION

While the occurrence of gas giant planets is a sensitive function of stellar metallicity, we find that the occurrence of debris discs does not have this same dependence. This suggests that construction of smaller planetesimal bodies, such as those found in the Kuiper Belt, does not require enhanced metallicity.

Both the planet–metallicity correlation and the absence of such a correlation for debris discs fit generally within the core accretion model for planet formation. Higher metallicity means that (for a fixed total disc mass) the amount of solid material will be higher. Pollack et al. (1996) found that increasing the surface density of solids by 50 per cent (equivalent to just +0.18 in [M/H]) reduced the time to form Jupiter from 8 to 2 Myr. The abundance of raw materials in a metal-rich protoplanetary disc increases the surface density and so accelerates the build-up of gas giant cores in the inner 10 au. When substantial cores can form while the disc is still in its early gas-rich phase ($\lesssim$10 Myr), they can accumulate thick gaseous envelopes and also migrate inwards due to the viscous drag of the gas. This can produce inner gas giants as observed. Recent models vary in detail, but for example, Kornet et al. (2005) find good agreement with the metallicity dependence of the rate of formation of gas giant planets in the core accretion scenario, and predict about three planets in our sub-solar metallicity base population, in good agreement with four planets so far detected. The general effect of higher solid abundance is to speed up core growth, and so there is much more time for giant planets to form and migrate before the disc disappears.

In contrast, core growth times are much longer in the outer disc, at several tens of au. If it can take $\sim$3 Gyr for a Pluto-sized core to form out at 100 au (Kenyon & Bromley 2004), the gas would have disappeared much earlier and so the planet could not have added an atmosphere. As long as boulder-sized bodies form quickly, settle to the mid-plane of the disc, and have fairly low collisional speeds by the time gas disperses, then planetesimals will continue to grow. Thus, planetesimals could still form even in a low-metal disc and their collisions could produce detectable debris. In this interpretation, the non-dependence of the debris phenomenon on metallicity is caused by the fact that the presence of planetesimals at late times is unaffected by their growth time-scale (which is metallicity-dependent), since it does not require the presence of large quantities of gas which we know from observations disappears relatively quickly. Debris discs are also believed to host planets at a few tens of au which clear their inner regions of dust and imprint structure on the discs (Greaves et al. 2004a). The presence of such planets is hardly surprising since we know significant grain growth must have occurred in these systems. Thus, the debris disc systems can be considered to be ‘extra’ planetary systems, for example, the 13 debris discs around sub-solar metallicity hosts that exist in addition to the four observed and expected (Kornet et al. 2005) inner giants. These planets form a different population to the radial-velocity planets, since they are probably orbiting too far out or are of too low mass to be detected in current radial-velocity experiments.

While the debris stars appear ‘generic’ in metallicity, this result cannot be inverted. That is, it is not true that all generic stars will be found to have a debris disc, as only $\approx$10 per cent of nearby Sun-like stars have dust detections. It is possible that most stars have a comet belt but that the dust produced in collisions is too low in mass to be detectable. The dust in the Kuiper Belt would be barely detectable beyond 1 pc (Greaves et al. 2004b), lying below the confusion limit even of large submillimetre telescopes. Our present study has shown that metallicity is not a factor in the production of large amounts of debris, and such a property of the system that does affect the presence of detectable debris remains to be determined. Better statistics in the future will enable us to test which properties do affect debris production; for example, several models exist for the time dependence of the debris phenomenon in which debris either is in a steady state, declines systematically with time, or is generated stochastically for short periods. This would be a fundamental step towards estimating the true planetesimal populations around nearby stars.

5 CONCLUSIONS

For a well-studied sample of Sun-like stars within 25 pc, the metallicity distribution of stars with debris discs matches that of stars in general, but stars with radial-velocity planets are significantly more metal-rich. The age distributions of the debris and planet stars are similar, so the trend is not due to a bias. The observations are generally consistent with a core growth model for planet formation, with faster planet growth where there is a high proportion of solid elements, while planetesimals form eventually on large orbits even for low metal content.

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