Young Stars & Planets Near the Sun
Proceedings IAU Symposium No. 314, 2015
J. H. Kastner, B. Stelzer, & S. A. Metchev, eds.
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doi:10.1017/S1743921315006201

Two-temperature Debris Disks: Signposts for Directly Imaged Planets?

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Abstract. This work considers debris disks whose spectra can be modelled by dust emission at two different temperatures. These disks are typically assumed to be a sign of multiple belts, but only a few cases have been confirmed via high resolution observations. We derive the properties of a sample of two-temperature disks, and explore whether this emission can arise from dust in a single narrow belt. While some two-temperature disks arise from single belts, it is probable that most have multiple spatial components. These disks are plausibly similar to the outer Solar System's configuration of Asteroid and Edgeworth-Kuiper belts separated by giant planets. Alternatively, the inner component could arise from inward scattering of material from the outer belt, again due to intervening planets. For either scenario, the ratio of warm/cool component temperatures is indicative of the scale of outer planetary systems, which typically span a factor of about ten in radius.

Keywords. circumstellar matter, planet-disk interactions

1. Introduction

Debris disks are a sign of successful planetesimal formation. The radial structure of most planetesimal belts is unknown; they may lie in multiple rings analogous to the Asteroid and Edgeworth-Kuiper belts, but may also be significantly extended in a way similar to gaseous protoplanetary disks (e.g. Kalas *et al.* 2005; Su *et al.* 2009). Because they are generally detected by excess emission above the photospheric level at infra-red (IR) wavelengths, and with high resolution imaging detections being relatively rare, discerning radial structure is in general difficult. The major difficulty is that the equilibrium temperature of a dust grain depends on both distance from the star and the size and optical properties of that dust grain. Thus, the radius of an unresolved debris disk cannot be unambiguously determined from the temperature of the observed emission, as the temperature is degenerate with the sizes of grains in the disk.

This contribution summarises some aspects of our study (Kennedy & Wyatt 2014) of debris disks whose spectral energy distributions (SEDs) require dust emission at two temperatures, and are perhaps indicative of dust that resides at a range of stellocentric distances. These systems have been of particular interest due to the popular interpretation that the two temperatures arise from two distinct dust belts (e.g. Chen *et al.* 2009; Morales *et al.* 2011). One question is then whether the intervening region between the two belts contains planets, and if so, whether dynamical clearing by these planets is the reason for two-belt structure. Circumstantial evidence for such a picture is given by systems with planets that reside between two dust components, such as HR 8799 and HD 95086 (Rameau *et al.* 2013; Moór *et al.* 2013).

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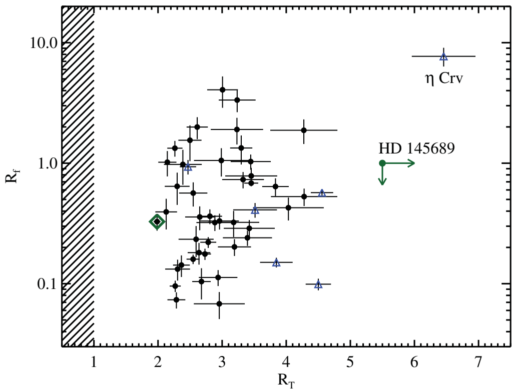

Figure 1. Two-temperature disk sample. Blue triangles note disks known two have multiple disk components from imaging and/or interferometry and the green diamond encloses HD 181327.

2. Two-temperature disk properties

One way to present two-temperature disks is the ratio of warm/cool component temperatures $\mathcal{R}_T$ and warm/cool component disk/star (fractional) luminosities $\mathcal{R}_f$, as shown in Fig. 1. Most two-temperature disks have fairly similar temperature ratios of 2-4, but with a range of fractional luminosity ratios. Warm components are detected with $\mathcal{R}_f$ down to about 0.1, and those fainter than this level become difficult to detect. Biases in the sample mean that the frequency of the two-temperature phenomenon is hard to estimate, but it appears fairly common, at the tens of percent level. A clear outlier is η Crv, with the largest temperature ratio, and one of several systems known from detailed observations to have two physically distinct dust belts.

The young F6 star HD 181327 (the dot enclosed by a green diamond in Fig. 1) is known to be concentrated in a narrow single belt. Lebreton *et al.* (2012) show that while the spectrum cannot be modelled with a single blackbody, allowing the composition of a single belt to vary can result in a good fit to the disk spectrum. Therefore, not all two-temperature disks necessarily originate from two distinct components.

3. Two temperatures = two belts?

Fig. 2 shows the temperature and fractional luminosity ratios against stellar temperature for our sample. In addition, the results from fitting two temperatures to model emission spectra calculated for single narrow dust belts are shown. These model grids were calculated for two different compositions and a range of dust size distributions, and the space covered by the red and blue lines shows where single narrow belts may masquerade as two belt systems due to significant dust emission at a range of temperatures.

Assuming that the minimum grain size is set by radiation pressure, two-temperature disks around A-type stars probably arise from multiple belts. A few two-temperature disks have been confirmed to have multiple belts by high resolution observations, and these comprise both A-type and Sun-like stars. For Sun-like stars, single belt models, particularly those with relatively flat size distributions, can produce two temperature disks, and this model is not conclusively ruled out because not all disks are resolved and/or detected at far-IR/mm wavelengths. Where imaging exists however, this model is disfavoured because the resolved disk size disagrees with that predicted. In addition, the flatter size distributions are steeper than those expected from collisional models and inferred from detailed modelling of well characterised systems. Therefore, in general, the assumption that two temperature disks have multiple belts should not be made without

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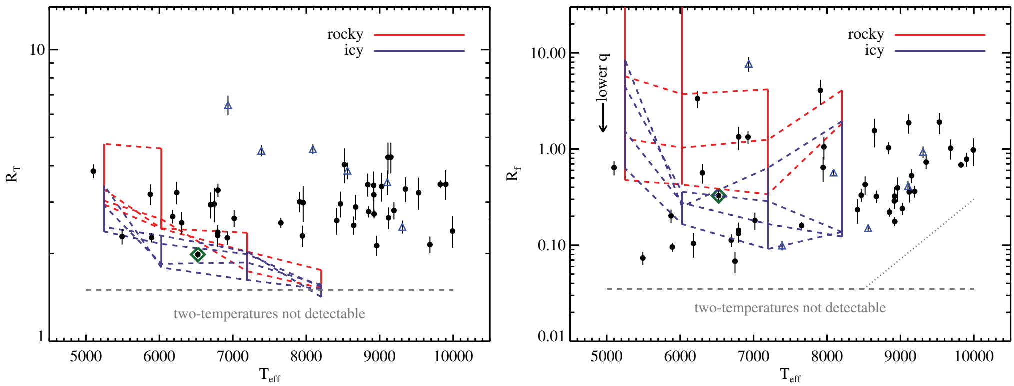

Figure 2. Two-temperature disk sample, with lines showing parameter space covered by single narrow belt models with "rocky" and "icy" compositions. Each vertex represents a model that resulted in a two-temperature disk.

considering the properties of those disks and their host stars, but it is likely that the bulk of two-temperature disks arise from multiple belts.

4. Evolution of multiple belts

A possible constraint on the origin of two-temperature disks could come from the expected collisional evolution. For example, if two-temperature disks arise from a single belt and the material compositions do not change, no significant evolution of $\mathcal{R}_f$ or $\mathcal{R}_T$ would be expected over time because the observed emission always comes from material in the same location. However, this similarity may also be expected if the warm belts are made of material delivered from the outer belt, perhaps scattered by planets (e.g. Bonsor & Wyatt 2012), in which case the brightness of the inner belt is reasonably connected to that of the outer one. On the other hand, if two temperatures arise from two independent belts (i.e. as in the Solar system), the two belts are expected to collisionally evolve at different rates. The collision rate in the disk depends strongly on orbital radius, and the brightness of a belt will start to decay when the largest objects start to collide, which will take longer for the outer belt. Therefore, for two belts that have the same initial brightness, the inner one will start to decay first, and the outer belt will follow later, and all other things being equal, in the long term the brightness difference between two belts is set by the difference in their radii.

Fig. 3 shows the evolution of $\mathcal{R}_f$ with time for our sample. No significant evolution is seen, which is suggestive of a comet delivery scenario. However, this lack of evolution does not strongly rule out the hypothesis that the two temperatures correspond to two distinct belts that are decaying due to collisions. The reason being that the warm belts are at sufficiently large radial distances that their brightness is not at odds with models of collisional evolution.

5. Planetary system structure

Our main conclusion is that most two-temperature debris disks comprise two disk components. Consideration of collisional models shows that these components could be two independent belts undergoing normal collisional evolution, analogous to the Solar System's Asteroid and Edgeworth-Kuiper belts. In other systems the inner components may also be linked to the outer belts via inward scattering of material by intervening

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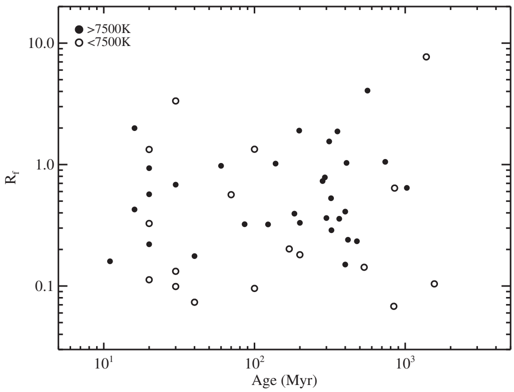

Figure 3. Dependence of $\mathcal{R}_f$ on stellar age. No trends are visible, but the ∼10 au radii of the warm components and their relatively slow collisional evolution means that the collisional two-belt scenario is not ruled out.

planets (e.g. Bonsor & Wyatt 2012). For either scenario, the ratio of warm/cool component temperatures is indicative of the scale of outer planetary systems, which typically span a factor of about ten in radius.

Acknowledgements

This work was supported by the European Union through ERC grant number 279973.

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Discussion

Song: How well can you constrain the width of the belts, for example could these systems actually just be single belts that are very wide?

Kennedy: It's very hard to tell just from the SED. However, in all cases where we've been able to obtain high-resolution images the inner belt is distinct from the outer one.

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