An infrared image of the dust disc around β Pic

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ABSTRACT

The star β Pictoris is a normal main-sequence star with a remnant disc of cool dust around it. We present observations of the β Pic dust disc in the far-infrared, obtained using the photometer (ISOPHOT) on the Infrared Space Observatory (ISO) satellite. We resolve the edge-on disc using high-resolution scans, with full widths at half-maximum of 8.7 × 2.9 arcsec2 (± 1.5 arcsec) at 25 μm (corresponding to a characteristic disc radius of 84 au) and 14.5 × 6.1 arcsec2 (± 2.0 arcsec) at 60 μm (corresponding to 140 au). The disc is just resolved in the minor axis direction at 60 μm. Photometry, from 4.85 to 200 μm, is combined with low-resolution spectroscopy and modelled to give an average dust temperature of 85 K, using a blackbody modified by an emissivity proportional to λ−1. A simple radiative transfer model is also used, with the grain radius ranging from 1 μm to 5 mm. The dust mass is estimated to be around (3–10) × 10−8 M⊙ (0.9–2.7 Mmoon), depending on the selected grain parameters.

Key words: circumstellar matter – stars: individual: β Pic – infrared: stars.

1 INTRODUCTION

The star β Pictoris is a nearby main-sequence star (A5 V), known to be surrounded by a disc of dust which emits thermal radiation in the infrared (Gillett 1986). Following its discovery with IRAS, the disc was imaged in scattered light at optical wavelengths by Smith & Terriile (1984) and others, and found to be edge-on. More recently the disc has been imaged in the near-infrared by Mouillet et al. (1997) and in the submillimetre by Holland et al. (1998), who determined a deconvolved size of 22 × 11 arcsec2 (± 3 arcsec) at 850 μm. Transient spectral signatures of infalling gas have been detected, and have been attributed by Lagrange-Henri, Vidal-Madjar & Ferlet (1988) to comets evaporating whilst falling on to the star. The dust disc has an inner dust-free cavity, a warp in the inner region of the disc, and asymmetry between the north-eastern and south-western sides [see Backman & Paresce (1993) and Kalas & Jewitt (1995) for more information]. By observing the dust in the infrared (and submillimetre), we can directly measure the disc properties, deriving the size and mass of the dust. The mass is found to be small, of the order of a lunar mass rather than an Earth mass.

The photometric and spectroscopic observations were taken as part of the ISOPHOT guaranteed time programme, and the high spatial resolution linear scans resulted from a special solicited ISO proposal, dedicated to the detailed investigation of β Pic. Calibration observations and observations of the background near β Pic were taken around the same time.

ISOPHOT is a unique instrument, able to resolve the edge-on disc using high-resolution scans, owing to the excellent pointing accuracy of ISO (about 1 arcsec). At 25 μm a set of eight scans were performed, at various angles to the major axis of the edge-on dust disc (see Fig. 1 and Table 1). Four scans were made at 60 μm (see Table 1), along the major and minor axes and at two intermediate angles. The step-size was 2 arcsec at 25 μm and 5 arcsec at 60 μm, making full use of the ISO pointing accuracy. Apertures were selected to match the step-size and resolution: 10 arcsec at 25 μm [diffraction limit full width at half-maximum (FWHM) 8 arcsec] and 23 arcsec at 60 μm (diffraction limit FWHM 19.2 arcsec). The scans at 25 μm were entered using the Calibration Uplink System instead of the normal observing templates (AOTs) because the step between sampling points was smaller than that allowed with AOTs. The full scan length was 56 arcsec at 25 μm and 140 arcsec at 60 μm. The disc is orientated at 30°, hence the scan made with ISO at 30° is along the major axis of the disc. Identical scans (at the same scan angles and for the same length of time) were made of HR 6705 (γ Dra), a point source calibration reference star with flux densities of 25.88 Jy at 25 μm and 4.55 Jy at 60 μm.

2 OBSERVATIONS

Observations of the β Pic dust disc in the far-infrared were obtained using the photometer (ISOPHOT) (Lemke et al. 1996) on the Infrared Space Observatory (ISO) satellite (Kessler et al. 1996).
The disc is orientated at 30°, hence the scan made with ISO at 30° is along the major axis of the disc. The error is ±2 arcsec at 60 μm and ±1.5 arcsec at 25 μm.

## 3 DATA REDUCTION

The data were reduced from the edited raw data (ERD) level using the ISOPHOT Interactive Analysis Software Package (pia) version 6.5 (Gabriel et al. 1997). The calibration is based on the general calibration files, version 3.1. Standard corrections for cold readout electronics non-linearity, de-glitching and signal derivation were applied. The impact of detector transients was minimized using drift detection. The data were converted into flux density units (Jy) using the 'fine calibration source' (FCS) calibration. After background subtraction, the nine pixels of the C100 camera (60–100 μm) were added up and the result corrected for the point spread function of the array. The data for the individual pointings of the C200 camera (120–200 μm) mini-maps were extracted and an average background flux derived and subtracted, and finally the value of the central pixel was used to derive the flux, again taking into account the point spread function factor.

The same processing steps were applied to the low-resolution spectroscopic data from 2.5 to 5 μm and 5.8 to 11.6 μm (taken with the ISOPHOT-S sub-instrument) as for the analysis of the photometric observations. However, the standard calibration file for converting the detector output signal into Jy (the spectral response function of ISOPHOT-S) was found to be inadequate for the flux range of β Pic. Therefore we used the 'dynamical spectral response correction' (Klaas et al. 1997). The calibration star HR 6817 (K1 III) was found to have the appropriate signal level over almost the full wavelength range of ISOPHOT-S, with 4.47 Jy at 4.8 μm falling to 0.98 Jy at 11.5 μm, so the spectral response function was constructed from the average of 10 observations of this star. Only for the longest wavelengths where β Pic showed a rising spectrum, and HR 6817 continued to fall, was there some mismatch in signal transient behaviour (resulting in a less satisfactory correction for the 9–11 μm region). The lower signal-to-noise ratio of HR 6817 in this wavelength range might also contribute to the flux discrepancy.

As the calibration for the photometry with the short-wavelength P1 detector (4.85–16 μm), using the FCS, did not yield satisfactory results, a special calibration procedure was performed using the same technique as was applied to the ISOPHOT-S data. Calibration observations of HR 7341 (K1 III) and HR 7633 (K5 II–III) were used, since these had similar flux densities to β Pic in the detector wavelength range, namely 4.40 and 44.0 Jy at 4.8 μm, and 1.02 and 10.7 Jy at 11.5 μm respectively.

The uncertainty in the flux density, estimated at wavelengths up to (and including) 16 μm, was 30 per cent. The uncertainty in the flux density estimated at wavelengths beyond 16 μm was 20 per cent.
from the Gaussian width (σ), we use a 4σ level to indicate the edge of the disc. The size of the disc from optical data is larger than the 4σ value from our infrared data, which gives a radius of 25 arcsec at 60 μm, the peak of the thermal emission from the dust.

Using a smooth local thin plate spline interpolation (Franke 1982), the eight calibrated high-resolution scans were mapped on to a 512x512 grid, using the individual positions (in astronomical coordinates) as reconstructed from the ISO satellite data, for both β Pic (Fig. 3, top left panel) and HR 6705 (the calibration star, representing the beam profile: Fig. 3, top right panel). This technique assumes that the profiles can be represented as Gaussian distributions. The bottom panel of Fig. 3 shows the result of 100 iterations of the maximum entropy deconvolution (Hollis, Dorband & Yusef-Zadeh 1992) of β Pic by HR 6705. The HST image shows a warp in the innermost part of the disc. Our deconvolved image suggests this warp, and the general asymmetry may continue to regions much further out in the disc, which would need confirmation with mid-infrared imaging. An asymmetry was predicted at 20 μm by Pantin, Lagage & Artymowicz (1997), from a model based on data at 10 μm. Kalas & Jewitt (1995) describe five types of asymmetry from their R-band data, one of which can be explained by the scattering geometry, so direct imaging would be important in tracking the warp from the inner disc, and in investigating the asymmetry further.

4.2 Photometry

Table 2 shows the flux densities derived for β Pic from the ISOPHOT photometric data, from 4.85 to 200 μm. The table also gives the values after colour correction (shown in Fig. 4). The ISOPHOT photometry agrees well with the IRAS photometry. The lower ISOPHOT-S value for the flux density at 11.3 μm reflects the smaller aperture (24 × 24 arcsec²), when compared with the photometry aperture (see Table 2), sampling less of the extended emission. The stellar properties of β Pic have been re-analysed in the light of the new distance (19.28 ± 0.19 pc) from Hipparcos (Crifo et al. 1997). Up to about 9 μm, the ISOPHOT-S data and the
two photometric data points (at 4.85 and 7.3 μm) can be interpreted as pure photospheric emission, and they are well represented by a Kurucz (1992) model, with \( T_{\text{eff}} \approx 8500 \) K and \( \log g \approx 4.5 \), absolutely calibrated using \( L/L_\odot = 8.9 \), \( R/R_\odot = 1.46 \), and the Hipparcos distance (19.28 pc). The far-infrared photometry shows the thermal emission from the dust, which is represented by a blackbody of 85 K modified by an emissivity law \( Q(\lambda) \sim \lambda^{-1} \). The model predicts a flux of 36 mJy at 800 μm, which agrees with the upper limit from Zuckerman & Becklin (1993) of 80 mJy, but is significantly lower than the flux found at 850 μm by Holland et al. (1998) with a peak flux of 58.3 ± 6.5 mJy per beam, and a total flux within a radius of 40 arcsec of 85.2 ± 10.0 mJy (which excludes a possible background feature in the south-west). The model predicts 10 mJy at 1300 μm; again it is lower than the value of 24.9 ± 2.6 mJy determined by Chini et al. (1991). Fig. 4 also shows a simple radiative transfer model, using silicate grains with sizes ranging from 1 μm to 5 mm, using a power-law distribution of \( n(a) \propto a^{-4.1} \), with \( a \) as the grain radius, and a surface density distribution \( \sigma \propto R^{-3} \), with \( R \) as the distance from the star. The ISOphoton and IRAS data between 8 and 24 μm show that there is an additional emission component, a mixture of thermal emission (with a temperature between about 300 and 500 K) and silicate dust emission [also observed by Knacke et al. (1993) and Aitken et al. (1993)], shown here by the rise in emission from 9 to 11.6 μm in Fig. 4. Emission by polycyclic aromatic hydrocarbons (PAHs) can be excluded, owing to the lack of emission features at 7.7 and 11.3 μm. Li & Greenberg (1998) have modelled the silicate feature using cometary dust models.

Figure 3. Contour plots have been constructed from the scan data at 25 μm. The images are 40 × 40 arcsec² in RA–Dec. The raw images of β Pic (top left) and HR 6705 (the calibration star, representing the beam profile: top right) are shown. The bottom panel gives the result of the deconvolution of β Pic by HR 6705. There are 10 contour levels shown, evenly spaced between the common maximum and minimum flux density values.
Each flux density is colour-corrected (CC) using either adjacent data points (from 4.85 to 16 \(\mu\)m) or with an 85-K blackbody (from 20 \(\mu\)m).

### 5 DISCUSSION

The flux in the cool (85 K) dust component, measured from 15 to 200 \(\mu\)m, is \(8.3 \times 10^{24}\) W (which corresponds to 0.022 \(L_\odot\)), so \(L_{\text{FIR}}/L_\odot = 0.0024\), similar to earlier estimates: for example Backman & Paresce (1993) quoted 0.003. Klaas & Elsa¨sser (1993) used the far-infrared luminosity and dust temperature to estimate dust mass; for \(\beta\) Pic we derive the dust mass to be \(10 \times 10^{8}\, M_\odot\) (or 2.7 \(M_{\text{moon}}\)). The dust mass can be estimated, using the slightly different assumptions of Becklin & Zuckerman (1990), to be \(3 \times 10^{8}\, M_\odot\) (0.9 \(M_{\text{moon}}\)). This range in mass shows that the mass depends on the assumptions used in the modelling, and in particular on the particle size distribution. Our radiative transfer model using silicate grains with sizes between 1 \(\mu\)m and 5 mm gives a reasonable fit to the far-infrared photometry and scan data, for a dust mass of \(8.6 \times 10^{8}\, M_\odot\) (2.3 \(M_{\text{moon}}\)), and with an inner radius to the dust disc of 71.3 au. The higher mass (7.8 \(M_{\text{moon}}\)), and larger disc radius, found from submillimetre observations (Holland et al. 1998) suggests that there is a significant, cooler outer region to the disc, seen in the submillimetre and not in the infrared.

The critical grain radius, using equation (5) in Backman & Paresce (1993), is estimated to be \(\sim 2.3\, \mu\)m; this small grain size agrees with the grain size derived by Aitken et al. (1993) of 2–3 \(\mu\)m, from their spectrum of the silicate dust feature. The critical grain radius for \(\beta\) Pic is much smaller than that derived (with ISOPHOT data in the same way) for Vega of 110 \(\mu\)m (Heinrichsen, Walker & Klaas 1997). The dust mass derived for \(\beta\) Pic is larger than that for Vega (0.3–1.5 \(\times 10^{8}\, M_\odot\), 0.08–0.4 \(M_{\text{moon}}\)) from Heinrichsen et al.

[Figure 4. The spectral energy distribution of \(\beta\) Pic. ISOPHOT photometric data are shown as plus signs (with the error bar representing the photometric error), the IRAS data as asterisks. The ISOPHOT-S low-resolution spectrum from 2.5 to 5 \(\mu\)m and 5.8 to 11.6 \(\mu\)m is shown as a solid line. The thin dot–dashed line gives the smoothed IRAS LRS spectrum of \(\beta\) Pic from the LRS data base. The dashed line from 1 to 9 \(\mu\)m shows the Kurucz model. The solid curve from 15 to 200 \(\mu\)m shows the model for the thermal dust emission, with a blackbody of \(T = 85\, K\) modified by an emissivity law of \(Q(\lambda) \propto \lambda^{-1}\). The ‘triple-dot–dashed’ line shows our radiative transfer model (including the Kurucz model), which used silicate grains with sizes between 1 \(\mu\)m and 5 mm.

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This is not included in our models. Knacke et al. (1993) compared the silicate dust feature in β Pic with data from Comet Halley and Comet Levy 1990XX, to show that the sharp bump at 11.2 μm could be attributed to crystalline silicates. Li & Greenberg (1998) showed that a good match to the data was achieved using crystalline clinoxyroxene or olivine (the model predicts features in the 30–50 μm region, which will assist greatly in deciding between these two silicates). They used their cometary dust models to derive a total dust disc mass for β Pic, and found a value of about 1 × 10^{-6} M_⊙ (27 M_⊕), an order of magnitude higher than the mass range derived from the infrared or submillimetre data.

The crystalline silicate feature, the warm thermal emission, and the observation of transient gas emission features, indicating falling bodies such as comets (Lagrange-Henri et al. 1988), all show how the β Pic system can maintain a population of small dust grains, which would be expected to be removed on a short timescale (Wolstencroft & Walker 1988). The dust mass that we derive is equivalent to at least 10^6 comets. According to Crifo et al. (1997), β Pic is on (or very close to) the zero-age main sequence; Crifo et al. conclude that the star is consequently at least 0.8 × 10^7 yr old. This is old enough for accretion towards a planetary system to have commenced, and our data suggest that β Pic could have a large ‘Oort’ cloud of comets around it.

6 SUMMARY
Using high-resolution scans we have resolved the dust disc around β Pic at 25 and 60 μm. The FWHM size at 25 μm is 8.7 × 2.9 arcsec^2 (± 1.5 arcsec), and at 60 μm it is 14.5 × 6.1 arcsec^2 (± 2.0 arcsec). These values correspond to characteristic radii of 84 au at 25 μm and 140 au at 60 μm, using the Hipparcos distance of 19.28 pc. We calculate L_{FIR}/L_⊙ = 0.0024, in agreement with earlier work, and we derive a dust mass of about 3–10 × 10^{-8} M_⊙ (0.9–2.7 M_⊕). Using thermal blackbody emission modified by an emissivity proportional to λ^{-1}, we determine T_{dust} = 85 K for the dust temperature. A simple radiative transfer model with a grain radius varying from 1 μm to 5 mm gives a dust mass of 8.6 × 10^{-8} M_⊙ (2.3 M_⊕) and an inner radius to the dust disc of 71.3 au. The scan data at 25 μm have been mapped into an image and deconvolved with HR 6705 to show that the structure in the inner disc, seen in the optical (the warp and asymmetry), may extend to larger distances in the infrared. We find no evidence, in the low-resolution spectrum, of emission features around 7.7 and 11.3 μm indicating PAH molecules. The data suggest that there is some warm dust (300 to 500 K) and a significant amount of cold dust in addition to the cool dust detected by ISO around β Pic.

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