A Herschel* resolved far-infrared dust ring around HD 207129

J. P. Marshall1, T. Löhne2, B. Montesinos3, A. V. Krivov2, C. Eiroa1, O. Absil4,⋆⋆, G. Bryden5, G. J. White19,20, and S. Wolf12

1 Departamento Física Teórica, Facultad de Ciencias, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain
c-mail: jonathan.marshall@uam.es
2 Friedrich-Schiller-Universität Jena, Astrophysikalisches Institut und Universitätssternwarte, 07743 Jena, Germany
3 Departamento de Astrofísica, Centro de Astrobiología (CAB, CSIC-INTA), ESAC Campus, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain
4 Institut d’Astrophysique et de Géophysique, Université de Liège, 17 Allée du Six Août, 4000 Sart Tilman, Belgium
5 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
6 ESA-ESAC Gaia SOC. PO Box 78 28691 Villanueva de la Cañada, Madrid, Spain
7 NASA Herschel Science Center, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA
8 UJF-Grenoble 1, CNRS-INSU, Institut de Planétologie et d’Astrophysique de Grenoble (IPAG) UMR 5274, 38041 Grenoble, France
9 European Space Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
10 UNINOVA-CA3, Campus da Caparica, Quinta da Torre, Monte da Caparica, 2825-149 Caparica, Portugal
11 NASA Goddard Space Flight Center, Exoplanets and Stellar Astrophysics, Code 667, Greenbelt, MD 20771, USA
12 Christian-Albrechts-Universität zu Kiel, Institut für Theoretische Physik und Astrophysik, Leibnizstr. 15, 24098 Kiel, Germany
13 Max-Planck Institute für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
14 John Hopkins University, Dept. of Physics and Astronomy, 3701 San Martin drive, Baltimore, MD 21210, USA
15 ESA Astrophysics & Fundamental Physics Missions Division, ESTEC/SRE-SA, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
16 INSA at ESAC. 28691 Villanueva de la Cañada, Madrid, Spain
17 Onsala Space Observatory, Chalmers University of Technology, 439 92 Onsala, Sweden
18 LESIA, Observatoire de Paris, 92195 Meudon Principal Cedex, France
19 Department of Physics and Astrophysics, Open University, Walton Hall, Milton Keynes MK7 6AA, UK
20 Rutherford Appleton Laboratory, Chilton OX11 0QX, UK

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ABSTRACT

Context. Dusty debris discs around main sequence stars are thought to be the result of continuous collisional grinding of planetesimals in the system. The majority of these systems are unresolved and analysis of the dust properties is limited by the lack of information regarding the dust location.

Aims. The Herschel DUNES key program is observing 133 nearby, Sun-like stars (<20 pc, FGK spectral type) in a volume limited survey to constrain the absolute incidence of cold dust around these stars by detection of far infrared excess emission at flux levels comparable to the Edgeworth-Kuiper belt (EKB).

Methods. We have observed the Sun-like star HD 207129 with Herschel PACS and SPIRE. In all three PACS bands we resolve a ring-like structure consistent with scattered light observations. Using a Boitís as a reference point spread function (PSF), we deconvolved the images, clearly resolving the inner gap in the disc at both 70 and 100 μm.

Results. We have resolved the dust-producing planetesimal belt of a debris disk at 100 μm for the first time. We measure the radial profile and fractional luminosity of the disc, and compare the values to those of discs around stars of similar age and/or spectral type, placing this disc in context of other resolved discs observed by Herschel/DUNES.

Key words. stars: individual: HD 207129 – circumstellar matter – infrared: stars

1. Introduction

Debris discs are composed of dust grains continuously produced by the collisional grinding of larger unseen planetesimals. This is inferred from the short lifetime of the dust grains compared to the age of the star (Backman & Paresce 1993) and suggest that the star around which they are observed has undergone a planetesimal formation process. In almost all cases, dust production is consistent with steady state attrition of the dust parent bodies (Löhne et al. 2008). The vast majority of debris discs are unresolved and we can only use modelling of the disc spectral energy distribution (SED) to determine the spatial location of the dust and the physical properties of the constituent dust grains. In the absence of independent information constraining
the spatial location of the dust, which introduces degeneracies into the fitting of the dust grain properties, e.g. between grain size and radial location, a standard dust composition is assumed. In the few examples of resolved debris discs, structures that imply the presence of a planetary mass body to maintain and sculpt the disc are frequently observed, e.g. warps, asymmetries and blobs (Golimowski et al. 2006; Kalas et al. 2005; Sherr et al. 2004). Planets may also be responsible for the inner cavities seen in resolved discs and inferred from the SEDs of unresolved ones (Wyatt 2008). The resolved disc structure can therefore be used as an indirect probe for exoplanets around such stars in regions of orbital radius/planetary mass parameter space that are otherwise inaccessible to traditional search methods (e.g. radial velocity, transits) and remain a challenge to direct imaging techniques.

HD 207129 (HIP 107649) was identified as having a debris disc by IRAS (Walker & Wolstencroft 1988) and followed up by both ISO and Spitzer (Jourdain de Muizon et al. 1999; Trilling et al. 2008). Extended emission from the disc has been seen in both scattered light (HST) and in thermal infrared emission (Spitzer MIPS70, Krist et al. 2010). The disc excess was also detected at 160 μm by both Tanner et al. (2009)and Krist et al. (2010), though with very different values (155 mJy cf 250 mJy), illustrating the need for Herschel PACS observations to constrain the disc SED. Additionally, the system has been identified as a promising candidate for exoplanet searches, due to its proximity (16 pc), age (1–3 Gyr) and the presence of an inner gap in the disc (Jourdain de Muizon et al. 1999; Beichman et al. 2010).

In this paper we present Herschel (Pilbratt et al. 2010) PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) observations of HD 207129. The large aperture Herschel telescope provides arcsecond resolution allowing detailed imaging of the debris disc in this system. In addition, greater precision and denser coverage of the disc SED can be obtained. Altogether, this allows better constraints to be placed on the disc’s SED and physical extent compared to previous observations, thereby allowing additional refinement of our models of this solar system analogue.

### 2. Observations and data reduction

HD 207129 was observed as part of the DUNES (Dust around NEarby Stars; Eiroa et al. 2010, Rodmann et al., in prep.) volume limited survey of nearby (<20 pc) Sun-like (FGK) stars. PACS scan map observations of the star were taken with both 70/160 and 100/160 channel combinations. Each scan map consisted of 10 legs of 3′ length, with a 4′ separation between legs, at the medium slow speed (20″/second). The target was observed at two position angles (70 and 110°) in both wavelength combinations. SPIRE small map mode observations were also carried out on a separate observation day (OD) covering a region ~4′ around HD 207129 at the nominal slow speed (30″/s). Using five repetitions of the scan map observations reduced the expected noise level to close to that of the expected extragalactic contribution (7–9 mJy at 250–500 μm) and increased the coverage of the central region of the map allowing pixel sizes smaller than the standard values to be used in the image reconstruction process (i.e. image scales of 4′′, 6′′ and 8′′ per pixel at 250, 350 and 500 μm, limited by the appearance of gaps in the image coverage near the centre of the map), which was useful for looking at extended structure in the source brightness profile. A summary of the observations is presented in Table 1.

#### Table 1. Summary of Herschel observations of HD 207129.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Observation ID</th>
<th>OD</th>
<th>Wavelengths [μm]</th>
<th>Duration [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACS</td>
<td>1342193163/64</td>
<td>322</td>
<td>70/160</td>
<td>276.0</td>
</tr>
<tr>
<td>PACS</td>
<td>1342193165/66</td>
<td>322</td>
<td>100/160</td>
<td>2250.0</td>
</tr>
<tr>
<td>SPIRE</td>
<td>1342209300</td>
<td>544</td>
<td>250/350/500</td>
<td>721.0</td>
</tr>
</tbody>
</table>

#### 2.1. Herschel photometry

PACS data reduction was carried out in HIPE 4.2 (the latest available public release¹), starting from the level 0 products using the standard reduction script. The separate scans at the two position angles of each channel pair were mosaiced to produce a final image at each wavelength. Image scales for the final mosiacs were 1″ per pixel for the blue (70/100 μm) images and 2″ per pixel for the red (160 μm) image. A high-pass filter was used to remove large scale background emission from the images, with filter widths of 15 and 25″ in the blue and red channels, respectively. A central region of 30″ radius in the images was masked from the high pass filter process to prevent the removal of any faint extended structure near to the source. SPIRE data reduction was also carried out in HIPE 4.2, again starting from the level 0 data using the standard script and processing options. The SPIRE maps were created using the naive scan mapper algorithm. The pixel scales for the SPIRE 250, 350 and 500 μm images from which photometry was taken were 6″, 10″ and 14″.

PACS fluxes were measured using aperture photometry carried out using the IDL APER routine. The aperture radius and sky annulus dimensions were 20″ and 30–40″, respectively. SPIRE fluxes were measured using an aperture of radius 30″ (due to the presence of several nearby sub-mm bright background objects), whilst the sky noise values were taken from Nguyen et al. (2010).

#### 2.2. Stellar parameters

HD 207129 (HIP 107649) is a nearby (d = 16 ± 0.2 pc, van Leeuwen 2007) star with a reported spectral type of G2V (from the Hipparcos catalogue, Perryman et al. 1997) or G0V (Gray et al. 2006). The bolometric luminosity has been estimated from the absolute magnitude and bolometric correction using measurements by Flower (1996). Our adopted values for the effective temperature, gravity and metallicity are derived from the mean of spectroscopic measurements from Santos et al. (2004), Valenti & Fischer (2005) and Sousa et al. (2008). Our own estimate of the rotational velocity, from high resolution spectra, is \( v \sin i = 3.71 \pm 1.81 \text{ km s}^{-1} \) (Maldonado et al., in prep.), consistent with estimates of Groot et al. (1996) and Torres et al. (2006).

Assuming the stellar inclination is that of the disc (i = 60 ± 5°, see Sect. 3.2) and the stellar radius is 1.07 R\( _{\odot} \) (estimated from the bolometric luminosity and effective temperature), the rotational period of the star is \( P = 12.6 \text{ days} \). The star is non-active, with measurements of the activity index, \( log R'_{HK} \), of −4.8 Henry et al. (1996) and −5.02 Gray et al. (2006), and a ROSAT X-ray luminosity \( log L_X/L_{bol} = −5.63 \).

The stellar mass estimated from the radius and gravity is 1.15 M\( _{\odot} \). From Padova evolutionary tracks (Girardi et al. 2002), a mass of 1.0–1.1 M\( _{\odot} \) and age of ~3.2 Gyr are obtained. This age is consistent with the activity index of Henry et al. (1996), using the calibration from Mamajek & Hillenbrand (2008).

¹ see: [http://herschel.esac.esa.int/HIPE_download.shtml](http://herschel.esac.esa.int/HIPE_download.shtml)
Conversely, the age derived from the rotational period using the same calibration is \( \sim 1.6 \) Gyr, which is consistent with the X-ray luminosity age of 1.8 Gyr using the relationship of Garcés et al. (2010), or the results of Giardino et al. (2008) (their Fig. 8). Other age estimates range from 0.6 (Song et al. 2003) to 6.0 Gyr (Lachaume et al. 1999; Valenti & Fischer 2005; Holmberg et al. 2009). We measure a LiI 6708 Å equivalent width of 35.5 \( \pm \) 3.3 mÅ (Maldonado et al., in prep.); this value, in conjunction with the estimate derived from the rotation period, points to an age greater than 600 Myr, implying the stellar age lies between these extremes. We therefore adopt an age in the range 1.5–3.2 Gyr as appropriate for HD 207129 (see Figs. 6 and 9, Maldonado et al. 2010). The stellar parameters and observational properties are summarised in Table 3.

The stellar photosphere contribution to the total flux was computed, using the stellar parameters, from a synthetic stellar atmosphere model interpolated from the PHOENIX/GAIA grid (Brott & Hauschildt 2005). Optical and near infrared photometry including Stromgren \( w_b \), Tycho-2 \( BV \) and \( HJK \) from Aumann & Probst (1991) constrain the stellar component of the SED, which has been scaled to the Spitzer IRS spectrum following the method of Bertone et al. (2004).

### 3. Results

#### 3.1. Disc spectral energy distribution

For the purposes of disc SED modelling, the PACS photometry was supplemented by a broad range of infrared and sub-millimetre observations including AKARI IRC all-sky survey 9/18 \( \mu \)m (Ishihara et al. 2010), Spitzer IRS spectrum and MIPS 24 and 70 \( \mu \)m photometry (Trilling et al. 2008), Spitzer 160 \( \mu \)m (Krist et al. 2010), APEX/LABOCA 870 \( \mu \)m (Nilsson et al. 2010) fluxes and upper limits from 450/850 \( \mu \)m JCMT/SCUBA (Sheret et al. 2004) and 1.2 mm SEST (Schütz et al. 2005) observations. The Herschel photometry and all complementary data are summarised in Table 2 (the upper limits are not quoted in the table because they were not used in the SED fitting process).

The disc SED, with the Herschel fluxes and ancillary photometry can be seen in Fig. 1. We have fitted the excess emission from HD 207129 with a standard black body model, modified beyond 210 \( \mu \)m by a factor of \( \beta = 1 \) (see Eq. (6), Wyatt 2008), from which estimates of the disc fractional luminosity and disc orbital radius were derived. The model was fitted to the infrared (both Herschel and ancillary) photometry through least squares minimisation weighted by the observational uncertainties. The best fit temperature \( T_{\text{disc}} = 50 \) K and fractional luminosity \( L_{\text{IR}}/L_{\text{bol}} = 8.3 \times 10^{-5} \) were obtained with a reduced \( \chi^2 \) of 1.34. Using the derived stellar parameters and the typical disc temperature, we calculate a dust orbital radius of 34 AU for black body emission, clearly much smaller than the resolved disc which would imply that a disc orbital radius larger than that derived from the black body modelling is required.

#### 3.2. Disc images

The disc of HD 207129 is clearly resolved in the PACS mosaics at all three wavelengths and is extended in the two shorter SPIRE wavelength maps. The optical position of HD 207129 is (in the epoch of the Herschel images) 21h48m16.05s –47°18′14.47″ (using proper motions from the re-reduction of Hipparcos, van Leeuwen 2007). In the PACS 70 \( \mu \)m image there is a peak in the disc brightness \( \sim 2'' \) NE from this position, consistent with the optical position within the Herschel pointing uncertainty, with a flux value consistent with the predicted stellar photosphere contribution. If this peak were the star, that would imply that the disc was asymmetric. In the deconvolution presented here, we have assumed that the star is at the centre of the disc, consistent with the symmetric scattered light disc observed in the HST results (Krist et al. 2010), and that the peak observed in the 70 \( \mu \)m image is a dust blob.

The disc size and position angle were measured by fitting a rotated ellipse to the source brightness profile contour of 3 times the sky noise value in the PACS images, whilst the disc inclination was measured from the ratio of the semi-minor to semi-major axes. A summary of these properties is in Table 4. The disc extent is the same in both the 70 and 100 \( \mu \)m images, though we would naively expect that the apparent disc size would increase due to the larger beam size and greater contribution from colder dust emission. We attribute the similar disc sizes to a
Table 3. Physical properties of HD 207129.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>16 ± 0.2 pc</td>
</tr>
<tr>
<td>Spectral type</td>
<td>G2V, G0V</td>
</tr>
<tr>
<td>V, B – V</td>
<td>5.57, 0.60 mag</td>
</tr>
<tr>
<td>Absolute magnitude</td>
<td>M_V, bolometric correction 4.55, –0.06</td>
</tr>
<tr>
<td>Bolometric luminosity, L_b</td>
<td>1.258 L_☉</td>
</tr>
<tr>
<td>Effective temperature</td>
<td>5912 K</td>
</tr>
<tr>
<td>Surface gravity, log g</td>
<td>4.44</td>
</tr>
<tr>
<td>Radius, R</td>
<td>1.07 R_☉</td>
</tr>
<tr>
<td>Metallicity, [Fe/H]</td>
<td>–0.01</td>
</tr>
<tr>
<td>Rotational velocity, v sin i</td>
<td>3.71 km s⁻¹</td>
</tr>
<tr>
<td>Rotation period, P</td>
<td>~12.6 days</td>
</tr>
<tr>
<td>Activity, log R'_{HK}</td>
<td>–4.80, –5.02</td>
</tr>
<tr>
<td>X-Ray luminosity, log L_X/L_b</td>
<td>–5.63</td>
</tr>
<tr>
<td>Mass, M</td>
<td>1.0–1.15 M_☉</td>
</tr>
<tr>
<td>Age</td>
<td>1.5–3.2 Gyr</td>
</tr>
</tbody>
</table>

Table 4. Measurement of the disc extent before (left – the HWHM of a Gaussian fitted to the source brightness profile) and after (right – the radial extent of annulus peak brightness) deconvolution, and the inclination and position angle of the disc at all three wavelengths.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>70 µm</th>
<th>100 µm</th>
<th>160 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis [&quot;]</td>
<td>14.5 9.0 14.0 9.0 17.0 8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-major axis [AU]</td>
<td>232 144 224 144 272 136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-minor axis [&quot;]</td>
<td>8.5 4.0 8.5 4.5 12.0 4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-minor axis [AU]</td>
<td>136 64 136 72 192.0 64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position angle [&quot;]</td>
<td>120 122 120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination [&quot;]</td>
<td>54 64 53 60 45 62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. (a) The disc position angles are the same in both original and deconvolved images. (b) The disc minor axis is not resolved at 160 µm in the original images.

The deconvolved radial extent of the disc was measured from the position of the peak brightness of the observed disc annulus along its major and minor axes. In the deconvolved 100 µm image, the measured radial extent was 9.0 ± 2.0 (144 ± 32 AU, see Fig. 2), with similar values from the 70 and 160 µm images. We measure the position angle of the disc to be 120 ± 5° through fitting via a least squares minimisation algorithm. From the ratio of the semi-major and semi-minor axes, the inclination to be 54 ± 5° (60 ± 5° in the deconvolved images). These results are consistent with previous HST measurements (Krist et al. 2010). We see no shift in the positional angle of the disc toward longer wavelengths.

Fig. 2. Radial profiles of HD 207129 along the semi-major (left) and semi-minor (right) axes of the disc. The red dotted lines are the measured profile either side of the disc centre along each axis; the solid red error bars mark the mean position at each point and the associated uncertainty. The grey line is the deconvolved disc profile and the black line is the subtracted stellar profile.

van Cittert) to check the suitability of the individual methods and the repeatability of any structure observed in the deconvolved images. It was found that all three methods clearly produced a ring structure in the deconvolved 70 and 100 µm images, though with varying noise patterns. Deconvolution of the 160 µm image via modified Wiener and van Cittert methods resulted in images with the disc structure as a pair of blobs either side of the stellar position. Using the Richardson-Lucy method the disc structure at 160 µm was recovered as a broken ring surrounding the stellar position with a clear central gap. We do not interpret the clumpy blobs in the deconvolved disc images as representing real structure in the debris disc. The result of the image deconvolution using the modified Wiener method can be seen in Fig. 3.

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Deconvolution was a two step process; the stellar photospheric contribution was removed from each image by subtraction of a PSF with a peak scaled to the predicted photospheric flux level in that image and centred on the stellar position determined from measurement of the 70 µm isophotes. The optical and isophote derived positions are in good agreement and the small offset between them does not impact upon the findings of this analysis.

After star subtraction, the image was deconvolved using three separate methods (modified Wiener, Richardson-Lucy and van Cittert) to check the suitability of the individual methods and the repeatability of any structure observed in the deconvolved images. It was found that all three methods clearly produced a ring structure in the deconvolved 70 and 100 µm images, though with varying noise patterns. Deconvolution of the 160 µm image via modified Wiener and van Cittert methods resulted in images with the disc structure as a pair of blobs either side of the stellar position. Using the Richardson-Lucy method the disc structure at 160 µm was recovered as a broken ring surrounding the stellar position with a clear central gap. We do not interpret the clumpy blobs in the deconvolved disc images as representing real structure in the debris disc. The result of the image deconvolution using the modified Wiener method can be seen in Fig. 3.

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3.3. Discussion

We have directly resolved the structure of a ring-like debris disc for the first time in the far infrared. The disc radial extent of $\sim 140$ AU is comparable to that of Fomalhaut (Kalas et al. 2005) or HD 107146 (Ardila et al. 2004).

The disc radius derived from the standard black body model, modified beyond 210 $\mu$m by a factor of $\beta = 1$, was 34 AU. This is a large underestimate of the true extent, in direct conflict with the resolved images. It serves to illustrate the dangers of modelling debris discs using only the SED and/or black body thermal emission models, which neither assume, nor tell you anything about, the dust grain optical properties (Wyatt 2008). Using a disc of dust grains that emit as modified black bodies and 10 $\mu$m dust grains, with a break shortward of the SED peak, the disc radius derived from the SED matches the observed images but fails to reproduce the sub-millimetre slope. The observed dust optical and thermal emission properties cannot be reconciled via Mie theory, either. A disc composed of small ($<1$ $\mu$m) dust grains would, according to Mie theory, reproduce the symmetric scattered light image, though the dust would then be too warm to reproduce the SED (Krist et al. 2010).

We measure a dust fractional luminosity of $8.3 \times 10^{-5}$, around six times greater than Vega ($1.5 \times 10^{-5}$, Habing et al. 2001) and half that of q1 Eri ($1.5 \times 10^{-4}$, Liseau et al. 2008). The value we measure is consistent with the fractional luminosity/age relation from Decin et al. (2003). The disc extent, $\sim 140$ AU, is larger than other DUNES resolved discs, e.g. q1 Eri (85 AU, Liseau et al. 2010) or $\zeta^2$ Ret (70–120 AU, Eiroa et al. 2010), but the derived black body temperature is also large, $\sim 50$ K, cf 60 K for the q1 Eri disc which is around an F star and 30–40 K for the $\zeta^2$ Ret disc which has a smaller extent around a star of similar spectral type.
A complete analysis of the disc SED and physical structure, in which both classical power-law particle size distribution models and a self-consistent collisional model are fitted to the available photometric and imaging data will be presented by Löhne et al. (in prep.).

4. Conclusions

We have presented Herschel PACS and SPIRE observations of HD 207129, the first to directly resolve the ring-like structure of a debris disc in both major and minor axes at far infrared wavelengths. The disc extent (140 ± 32 AU), inclination (51 ± 5°) and typical (black body) temperature (∼50 K), derived purely from the observations assuming no particular grain model, are similar to previous measurements. Compared to other discs around stars of similar spectral type and age, the disc of HD 207129 is both larger and warmer (for the observed size), though it is not completely atypical in either respect, but situated at the margins of the known range of disc morphologies. A simple analysis based on a black body model has been proved unrealistic. A more detailed self-consistent study is left for future work (Löhne et al., in prep.).

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