Cold DUst around NEarby Stars (DUNES). First results*

A resolved exo-Kuiper belt around the solar-like star $\zeta^2$ Ret


(Affiliations are available in the online edition)

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ABSTRACT

We present the first IR observations of the solar-type stars $\delta$ Pav, HR 8501, 51 Peg and $\zeta^2$ Ret, taken within the context of the DUNES Herschel open time key programme (OTKP). This project uses the PACS and SPIRE instruments with the objective of studying infrared excesses due to exo-Kuiper belts around nearby solar-type stars. The observed 100 $\mu$m fluxes from $\delta$ Pav, HR 8501, and 51 Peg agree with the predicted photospheric fluxes, excluding debris disks brighter than $L_{dust}/L_\star \approx 5 \times 10^{-7}$ (1$\sigma$ level) around those stars. A flattened, disk-like structure with a semi-major axis of $\sim 100$ AU in size is detected around $\zeta^2$ Ret. The resolved structure suggests the presence of an eccentric dust ring, which we interpret as an exo-Kuiper belt with $L_{dust}/L_\star \approx 10^{-3}$.

Key words. stars: general – planetary system – space vehicles: instruments

1. Introduction

The discovery of infrared excess emission produced by cold, optically thin disks composed of micron-sized dust grains around main sequence stars is one of the main contributions of IRAS (Aumann et al. 1984). Since the lifetime of such grains, set by destructive collisions, Poynting-Robertson drag and radiation pressure, is much shorter than the ages of these stars, one must conclude that those dust disks – called debris disks – are continuously replenished by collisions of large rocky bodies (Backman & Paresce 1993). Observations of debris disks provide powerful diagnostics from which to learn about the dust content, its properties and its spatial distribution; in addition, since dust sensitively responds to the gravity of planets, it can be used as a tracer of the presence of planets. Thus, observations of debris disks around stars of different masses and ages inform us about the formation and evolution of planetary systems, since they are a direct proof for the existence of planetesimals and an indirect tracer of the presence of planets around stars.

In the Solar System, the asteroid and Kuiper belts are examples of debris systems; in particular, the Kuiper belt has an estimated dust luminosity $L_{dust}/L_\star \sim 10^{-7}$–$10^{-6}$ (Stern 1996). IRAS was only able to detect bright disks, $L_{dust}/L_\star > 10^{-4}$, mainly around A and F stars; ISO extended our knowledge to a wider spectral type range and found a general decline with the stellar age (Habing et al. 2001; Decin et al. 2003). A remarkable step forward has been achieved by Spitzer, studying debris disks as faint as $L_{dust}/L_\star$ several times 10$^{-7}$, their incidence from A to M type stars, the age distribution, the presence of planets, etc. (e.g. Su et al. 2006; Trilling et al. 2008; Bryden et al. 2009). Spitzer has, however, several limitations. Its poor spatial resolution prevent us from studying fundamental disk parameters which require resolved imaging, and the confusion limit inherent in its large beam limits its detection capability to cold disks brighter than the Kuiper belt by around two orders of magnitude. Also, Spitzer is not sensitive longward of 70 $\mu$m, wavelengths particularly important for the cold disks generally found around Sun-like stars. The far-infrared 3.5 m diameter Herschel space telescope (Pilbratt et al. 2010) with its instruments PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) overcomes these limitations, offering the possibility of characterising cold, $\sim 30$ K, debris disks as faint as $L_{dust}/L_\star$ few times 10$^{-7}$ with spatial resolution $\sim$50 AU at 10 pc, i.e., true extra-solar Kuiper belts.

DUNES$^1$ is a Herschel OTKP designed to detect and characterize cold, faint, debris disks, i.e., extra-solar analogues to the Kuiper belt, around a statistically significant sample of main-sequence FGK nearby stars, taking advantage of the unique capabilities of Herschel with PACS and SPIRE. The data will be analysed with radiative, collisional and dynamical dust disk models. A complete description of DUNES goals, 

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*A Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

1 DUNES around NEarby Stars, http://www.mpia-hd.mpg.de/DUNES/
Table 1. Summary of the SDP DUNES observations.

<table>
<thead>
<tr>
<th>Star</th>
<th>Obs. ID</th>
<th>Mode(^1)</th>
<th>Bands</th>
<th>Scan Direction</th>
<th>OT (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>q(^1)Eri</td>
<td>1342187139/40 SM</td>
<td>100/160</td>
<td>63°/117°</td>
<td>2536</td>
<td></td>
</tr>
<tr>
<td>q(^1)Eri</td>
<td>1342187141 PS</td>
<td>100/160</td>
<td>4714</td>
<td></td>
<td></td>
</tr>
<tr>
<td>q(^1)Eri</td>
<td>1342187142 PS</td>
<td>70/160</td>
<td>789</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ζ(^2)Ret</td>
<td>1342183660 PS</td>
<td>100/160</td>
<td>1572</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ζ(^2)Ret</td>
<td>1342191102/03 SM²</td>
<td>100/160</td>
<td>117°/63°</td>
<td>4510</td>
<td></td>
</tr>
<tr>
<td>ζ(^2)Ret</td>
<td>1342191104/05 SM²</td>
<td>70/160</td>
<td>63°/17°</td>
<td>4510</td>
<td></td>
</tr>
<tr>
<td>δPav</td>
<td>1342187075/06 SM</td>
<td>100/160</td>
<td>45°/135°</td>
<td>3841</td>
<td></td>
</tr>
<tr>
<td>HR8501</td>
<td>1342187145/46 SM</td>
<td>100/160</td>
<td>63°/117°</td>
<td>1890</td>
<td></td>
</tr>
<tr>
<td>51Peg</td>
<td>1342187225 PS</td>
<td>100/160</td>
<td>1731</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. (\(^1\) SM = scan map; PS = chop-nod/point-source mode; \(^2\) routine phase DUNES observing time (not SDP))

target selection, and stellar properties will be presented elsewhere (Eiroa et al., in prep.). The objectives of the DUNES survey are complementary to those of the OTKP DEBRIS (Matthews et al. 2010). Both projects have complementary star samples, sharing partly some sources and the corresponding data.

The DUNES objectives require the detection of very faint excesses at the mJy level, comparable to the photospheric emission and only a few times the measurement uncertainties. The primary observing strategy is designed to integrate for as long as needed to detect the 100 μm photospheric flux, subject only to confusion noise limitations. In this letter we present our first results obtained during the science demonstration phase (SDP) of Herschel. Four solar-type G stars were observed: ζ\(^2\)Ret, δPav, HR8501, and 51 Peg. We also observed q\(^1\)Eri as a test object with a well-known, bright debris disk; the q\(^1\)Eri results are presented in an accompanying letter (Liseau et al. 2010). Excluding δPav, the rest of the stars are shared targets with DEBRIS.

2. Observations and data reduction

The stars were observed with PACS at 70 μm (blue), 100 μm (green), and 160 μm (red). Two observing modes were used – chop-nod/point-source (PS hereafter) and scan map (SM hereafter). Our data set allows us to make a direct comparison of both modes, specially in the cases of q\(^1\)Eri and ζ\(^2\)Ret. A critical evaluation of this comparison will be the subject of a technical note. SM observations of ζ\(^2\)Ret were carried out as DUNES routine observations. Table 1 gives some details of the observations including the identification number, the observing mode, the wavelength bands, the scan direction angles, and the total duration of the observation (OT).

Data reduction was carried out using the Herschel interactive processing environment (HIPE), version v2.0.0 RC3, and the pipeline script delivered at the December 2009 Herschel data reduction workshop, ESAC, Madrid, Spain. The script provides all the tools to convert pure raw PACS/Herschel data to flux calibrated and position rectified images. While the instrument pixel size is 3′′×2′′ for the blue and green bands and 6′′×4′′ for the red band, the resolution of the final images is set to 1′′/pixel and 2′′/pixel for the blue/green and red bands, respectively.

3. Results

3.1. δ Pav, HR 8501, 51 Peg

Table 2 gives J2000.0 equatorial coordinates of δ Pav, HR 8501 and 51 Peg at 100 μm, as well as their optical positions. PACS positions are corrected from the proper motions of the stars. Differences between the optical and 100 μm positions are within 9×10⁻⁵ Jy/pixel for the 100 μm SM data of δ Pav and HR 8501, respectively. The sky noise is considerably higher in the PS-mode 51 Peg image (≈4.3×10⁻⁵ Jy/arcsec²) due to the very irregular background and presence of negative signals. The 160 μm sky noise was 4.9×10⁻⁵ Jy/pixel for the δ Pav data. The absolute calibration uncertainties are 10% in the blue and green bands and better than 20% in the red band.

3.2. ζ\(^2\)Ret (HIP 15371)

Figure 1 shows the SM PACS images of ζ\(^2\)Ret. An East-West oriented structure is seen at 70 and 100 μm. It consists of two point-like flux peaks embedded in a faint, extended emission, which displays a secondary diffuse maximum at its Western side. Both point-like peaks have similar brightness in the green band, but the Eastern point-like peak is much fainter in the blue band. The two point-like sources are unresolved in the lower-resolution 160 μm image; instead a single bright peak is observed at that position with a secondary maximum at the position of the 70/100 μm Western diffuse emission.

Table 3 gives positions at 70 and 100 μm of both point-like sources, and of the brightest 160 μm peak; the optical position of ζ\(^2\)Ret is also given for comparison. The brightest 70 μm peak coincides with the optical position of the star within the Herschel pointing error; this result and the fact that its PACS 70 and 100 μm fluxes are similar to the expected ζ\(^2\)Ret photospheric fluxes (see below) lead us to identify this point-like PACS object with the optical star. There is a small shift between the 70 and 100 μm positions of ζ\(^2\)Ret, but we note that a similar shift is found for other field objects – a blue object very close to the ζ\(^2\)Ret complex towards the South-West; and two red objects, one towards the Northwest and one towards the Northeast (see Fig. 1).

The middle panels of Fig. 1 show isophote plots. The optical position of ζ\(^2\)Ret is marked. 100 μm and 160 μm contours have been spatially shifted so that the peak positions of the mentioned field objects coincide in all three bands (those objects are not shown in the isochrone plots). The size of the whole structure changes with wavelength from ≈25″×15″ in the blue to ≈40″×15″ in the red band. East-West intensity profiles are shown in the bottom of Fig. 1, together with similar profiles of α Bootis. The blue and green intensity profiles show the point-like character of ζ\(^2\)Ret, as well as of the faint peak at the East, called PS-E hereafter; the profile in the red band also shows point-like behaviour for the brightest 160 μm peak, ζ\(^2\)Ret+PS-E in Fig. 1.
Table 2. Equatorial coordinates, FWHM at 100 μm, observed fluxes with 1σ statistical errors (FPACS), and predicted photospheric fluxes (F∗).

<table>
<thead>
<tr>
<th>Star</th>
<th>Optical position (J2000)</th>
<th>PACS 100 μm position (J2000)</th>
<th>PACS 100 μm FWHM</th>
<th>F_PACS 100 μm</th>
<th>F∗ 100 μm</th>
<th>PACS 160 μm FWHM</th>
<th>F_PACS 160 μm</th>
<th>F∗ 160 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ Pav</td>
<td>20:08:43.61 −66:10:55.4</td>
<td>20:08:43.53 −66:10:58.1</td>
<td>6′3 × 6′2</td>
<td>59.6 ± 1.1</td>
<td>68.7</td>
<td>21.0 ± 1.5</td>
<td>26.9</td>
<td></td>
</tr>
<tr>
<td>51 Peg</td>
<td>22:57:27.98 +20:46:07.8</td>
<td>22:57:28.44 +20:46:08.5</td>
<td>5′9 × 6′0</td>
<td>11.3 ± 1.7</td>
<td>10.8</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes. Absolute PACS uncertainties are ~10% and less than 20% for 100 and 160 μm, respectively. Flux units are mJy.

Fig. 1. PACS results of c2 Ret. Panels from left to right: 70 μm, 100 μm, and 160 μm. Upper panel: field size is 100′′ × 100′′ with East to the left and North up. Middle panels plot isocontours. Note that the field size is different from that displayed in the upper panels. The “star” symbol, position (0,0), corresponds to the optical star (Table 3). A segment indicating 120 AU is shown. Contours: 70 μm: 3, 4, 6, 9, 12, 15, 24 σ, 100 μm: 3, 4, 5, 6, 12, 14 σ, 160 μm: 3, 6, 9, 12, 15, 18 σ (1σ values are indicated in the text). Lower panels: RA intensity profiles through the peak flux of c2 Ret (solid line). For comparison, RA intensity profiles of the calibration star α Bootis are also plotted (dashed lines), scaled to the peak flux of c2 Ret (70 and 100 μm) and c2 Ret+PS-E (160 μm). The α Bootis profile is also scaled and superimposed to PS-E in the 100 μm panel.

and Table 3. The Western diffuse peak (“W” in Fig. 1) appears very prominent in the green and red profiles, while it is very faint compared to c2 Ret in the blue profile. North-South profiles (not shown) do not resolve either c2 Ret, PS-E, or c2 Ret+PS-E in any band, i.e. they are point-like along that direction with no hint of any faint extended emission.

Table 3 gives PACS fluxes estimated using the flux peaks of the point-like sources and integrating over beam sizes given by $\pi (FWHM_x \times FWHM_y) / 4 \ln 2$. The PACS source identified with c2 Ret is a blue object, while PS-E is a red one. The flux at 160 μm corresponds to c2 Ret+PS-E, but PS-E is the main contributor to the flux at this wavelength – the emission is peaking more towards PS-E (Fig. 1). The total flux of the c2 Ret complex is 44.5 mJy, 40.4 mJy, and 42.6 mJy in the blue, green and red bands, respectively. The estimated 70 μm flux for the whole complex agrees very well with the unresolved Spitzer flux of 46 mJy at the same wavelength (Trilling et al. 2008).

Table 3. Coordinates, fluxes, and 1σ statistical errors of the c2 Ret PACS point-like sources. Flux units are mJy.

<table>
<thead>
<tr>
<th>Object</th>
<th>α(2000.0)</th>
<th>δ(2000.0)</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>c2 Ret (optical)</td>
<td>03:18:12.82</td>
<td>−62:30:22.9</td>
<td></td>
</tr>
<tr>
<td>c2 Ret (70 μm)</td>
<td>03:18:12.77</td>
<td>−62:30:23.2</td>
<td>24.9 ± 0.8</td>
</tr>
<tr>
<td>c2 Ret (100 μm)</td>
<td>03:18:13.12</td>
<td>−62:30:24.4</td>
<td>13.4 ± 1.0</td>
</tr>
<tr>
<td>PS-E (70 μm)</td>
<td>03:18:13.65</td>
<td>−62:30:24.2</td>
<td>8.9 ± 0.8</td>
</tr>
<tr>
<td>PS-E (100 μm)</td>
<td>03:18:13.55</td>
<td>−62:30:24.4</td>
<td>13.5 ± 1.0</td>
</tr>
<tr>
<td>c2 Ret+PS-E (160 μm)</td>
<td>03:18:13.37</td>
<td>−62:30:23.2</td>
<td>19.4 ± 1.5</td>
</tr>
</tbody>
</table>

4. Discussion

Our data do not reveal any cold dust disk around δ Pav, HR 8501 or 51 Peg, since the observed and predicted 100 μm photospheric fluxes coincide within the uncertainties (Table 2). Assuming dust temperatures of 40 K (peak blackbody fluxes at ~100 μm), we
can exclude debris disks with $L_{\text{dust}}/L_* \geq 5 \times 10^{-7}$ ($1\sigma$) (Eq. (4) from Beichmann et al. 2006).

$\zeta$ Ret, located at 12 pc, is a G1 V star with a bolometric luminosity of 0.97 $L_\odot$ and an estimated age of ~2–3 Gyr (Eiroa et al., in prep.). Figure 2 shows the stellar SED as well as PACS fluxes from PS-E and the whole complex; a PHOENIX stellar photosphere (Brott & Hauschildt 2005) is also plotted. The agreement between the observed 70 and 100 $\mu$m fluxes from the blue bright point-source and those predicted by the photospheric fit, 24.7 mJy and 12.1 mJy at 70 and 100 $\mu$m, respectively, is excellent. This photometry and its positional alignment with the stellar position support our claim that the PACS blue point-like object is indeed $\zeta$ Ret. On the other hand, the nature of the extended structure is intriguing. While coincidental alignments with background objects are common in IRAS all-sky images, the much higher resolution of Herschel makes such juxtapositions unlikely within a targeted survey. Based on Spitzer source counts of background galaxies at 70 $\mu$m (Dole et al. 2004), we find that the probability of chance alignment with a $\geq 20$ mJy source within $10''$ is just $10^{-3}$.

The source PS-E is a red object with a black body temperature $T(70-100 \mu m) \approx 40$ K. We have pointed out that both PS-E and $\zeta$ Ret are not resolved at 160 $\mu$m and that the flux peak at this wavelength is closer to PS-E. If we subtract from the measured 160 $\mu$m flux the stellar flux predicted for $\zeta$ Ret (4.7 mJy) and make the plausible assumption that the residual flux (14.7 mJy) originates in PS-E, this 160 $\mu$m flux for PS-E is again consistent with a $\approx 40$ K blackbody. While $\zeta$ Ret is clearly not stellar; we suggest that it is instead orbiting circumstellar dust. The contribution of the extended emission to the total flux can be estimated subtracting the point-like sources from the total flux reported above. The residual flux mainly corresponds to the Western diffuse emission since the point-like sources are not resolved along the North-South direction. In this case, the remaining flux corresponds to black body temperatures in the range $\approx 30-40$ K, and the total fractional luminosity from the entire structure surrounding $\zeta$ Ret is $L_{\text{dust}}/L_* \approx 10^{-5}$.

We have the interesting scenario of a G1 V star surrounded by optically-thin 30–40 K emission. This is the temperature range expected for black body dust grains orbiting at distances $\sim 100$ AU from the star. This is consistent with the projected linear distances from $\zeta$ Ret to PS-E and to the Western diffuse emission of $\sim 70$ AU and $\sim 120$ AU, respectively. The red image suggests a flattened, disk-like structure with the star located asymmetrically along the major axis, while the blue and green images suggest it is ring-like given the flux cavity towards the West from the star. We interpret the structure in the PACS image as a dust ring surrounding $\zeta$ Ret. We attribute the observed East-West asymmetry to a significant disk eccentricity - $e \approx 0.3$. Similarly, an offset is observed in the Fomalhaut debris disk with $e \approx 0.1$ (Stapelfeldt et al. 2004). Maintaining a stable eccentric ring requires an external driving force such as a shepherding planet (Wyatt et al. 1999) and in the case of Fomalhaut the predicted planet has been been directly imaged (Kalas et al. 2008). The disk asymmetry in the $\zeta$ Ret system may likewise be the signature of an unseen planetary companion. While this is an exciting possibility, other forces might also produce disk asymmetry. For example, interaction with the ISM is probably responsible for the strong asymmetry observed around HD 61005, since its brightness offset is well aligned with the star’s space motion (Hines et al. 2007). A more profound analysis and detailed modeling of $\zeta$ Ret and the suggested Kuiper belt is deferred to a future paper.

5. Conclusions

Our results show the capability of Herschel/PACS to detect and resolve cold dust disks with a luminosity close to the solar Kuiper belt, which will allow us to deepen our understanding of planetary systems, in particular those associated with mature stars. Specifically, our data exclude the existence of cold debris disks with $L_{\text{dust}}/L_* \geq 5 \times 10^{-7}$ ($1\sigma$) around the solar-type stars δ Pav, HR 8501 and 51 Peg. On the other hand, the data show that $\zeta$ Ret is a good example where cold disks around nearby stars, very much alike the solar Kuiper belt, can be resolved and studied in great detail with the Herschel space observatory.

References
