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DUst around NEarby Stars (DUNES): searching for Kuiper-belt analogues around solar-type stars

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Abstract

In this paper we summarize some of the results of the *Herschel* Open Time Key Programme DUNES (DUst around NEarby Stars). This project aims at detecting and studying cold dust discs, i.e. Edgeworth-Kuiper-belt analogues, around FGK stars of the solar neighbourhood, in a volume-limited sample. The sensitivity and wavelengths of the two instruments used, namely PACS (70, 100 and 160 μm) and SPIRE (250, 350 and 500 μm) are the appropriate ones for these tasks. Despite of the fact that, at the time of writing these proceedings, only about half of the sample has been observed, new results and increased statistics with respect to previous surveys and observations have emerged. Some new, unexpected results, in the form of very cold discs, pose some challenges to the current modelling paradigms. *Note that at the time this paper is published, the results given and some of the conclusions will be obviously out of date.*

1 Introduction

The discovery of infrared (IR) excesses around main-sequence (MS) stars such as Vega, Fomalhaut and β Pic, made in the early 1980s by the *IRAS* satellite, came as a big surprise [1]. Since the lifetimes of dust grains against radiative/wind removal and collisional disruption are much shorter than the ages of these stars, one must conclude that these mature stars are surrounded by significant amounts of circumstellar dust which is not primordial, but rather is produced by ongoing processes. These discs are called "debris discs".

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In any debris disc model, dust production results from collisional events within a substantial population of larger bodies. For a handful of objects, resolved imaging has provided confirmation that debris discs generally resemble dust belts, with peak densities at tens to hundreds of AU from the central star and estimated masses from (sub-)millimetre unresolved observations as low as 10^{-3} $M_{\oplus}$. The asteroid belt and the Kuiper belt (also known as the Edgeworth-Kuiper belt, EKB hereafter) are examples of debris discs in our Solar System. If the EKB could be observed from afar, it would appear as a cold ($\sim$ 30–40 K), extended (up to $\sim$ 100 AU) and faint ($L_{\rm dust}/L_{\odot} \sim 10^{-7} - 10^{-6}$, [12]) dust disc with a huge central hole caused by the most massive planets [9].

Since the discovery of debris discs, many new observational results and theoretical insights have been obtained from IR and (sub-)millimetre photometry. *IRAS* originally found that about 10% of early MS stars (A and F) had an excess at 60-100 μm in the range $10^{-5} < L_{\rm dust}/L_{*} < 10^{-4}$. *ISO* provided important information on age distribution of debris discs, finding a rapid fall-off in incidence as age increases [7, 3]. *Spitzer* has added a wealth of new information in recent years, studying debris discs as faint as $L_{\rm dust}/L_{*} <$ several times 10^{-6}: a $15 \pm 3\%$ detection rate for IR excess at 70 μm around F5-K5 mature (> 1 Gyr) stars [2, 15]; a higher incidence of dust emission for type A stars [13] and a lower incidence for M stars [5]; and a marginally higher incidence around binary stars [14]. *Spitzer* has, however, several limitations. Its poor spatial resolution prevents us from constraining fundamental disc parameters which require resolved imaging, and the confusion limit inherent to its large beam limits its detection capability to cold discs brighter than the Kuiper belt by around two orders of magnitude. Also, Spitzer is not sensitive longward of 70 μm, wavelengths particularly important for the cold discs generally found around Sun-like stars. The far-infrared 3.5 m diameter *Herschel* space telescope [10] with its instruments PACS [11] and SPIRE [6] overcomes these limitations, offering the possibility of characterising cold, $\sim$ 30 K, debris discs as faint as $L_{\rm dust}/L_{*} <$ few times 10^{-7} with spatial resolution $\sim$ 30 AU at 10 pc, i.e., true extra-solar EKBs.

2 The DUNES project

DUNES is a Herschel Open Time Key Programme (OTKP) designed to detect and characterise cold, faint, debris discs, 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 disc models. The objectives of the DUNES survey are complementary to those of the OTKP DEBRIS [8]. Both projects have complementary star samples, sharing some sources and the corresponding data. Other additional goals are the study of the dependence of the formation of planetesimals on stellar mass, collisional and dynamical evolution of the exo-EKBs, the presence of debris discs compared to the presence of planets, and the properties of the dust and size distribution in the exo-EKBs. The overall aim is the understanding of the formation and evolution of planetary systems.

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. Note that the minimum photospheric flux at 100 μm we are dealing with is around 4 mJy and that an analogue to our EKB placed at 10 pc, would emit 7–10 mJy at that wavelength.

The sample contains 133 stars with spectral types FGK stars at a distance less than 20 pc. Also, all the stars with known planet candidates at less than 25 pc and all the stars with debris discs at less than 25 pc discovered by *Spitzer* are included.

Apart from the intrinsic problems of the reduction of the observations themselves, issues such as confusion and casual alignment of sources are being taking carefully into account in order not to missinterpret some results. Confusion in particular is an important limitation, it can be caused by extragalactic objects in the field, other field stars or extended structures such as cirri.

3 Results

Table 1 shows a summary of the outcome of the project until September 2010. As we mention in the abstract, those results will be obviously out of date when this paper is published, so we refer the reader to recent publications for a detailed an updated account of results. In slanted characters we give the numbers corresponding to new detections. Note in particular the discovery of a new type of cold discs (see below) which pose interesting challenges to their interpretation.

Table 1: Results until September 2010

	F-type	G-type	K-type	Total
Observed	11	21	18	50
No excess	5	13	12	30
Excess *(new)*	6 *(1)*	7 *(3)*	4 *(4)*	17 *(8)*
Resolved *(new)*	3 *(2)*	4 *(3)*	1 *(1)*	8 *(6)*
Cold discs	*1*	*3*	*4*	*8*
+Planets	1	3	2	6
Peculiar		1	2	3

3.1 SED diversity

Among the 50 stars observed by September 2010, a variety of spectral energy distributions (SEDs) has been found. In this subsection we show some of them along with a qualitative description of the structure that can be the origin of each particular SED.

Figure 1 (left) shows a typical example of a SED without excesses at any of the PACS wavelengths, i.e. it corresponds to a star without a disc or with dust emitting below the sensitivity levels of the instrument: the three PACS measurements lie on the photospheric

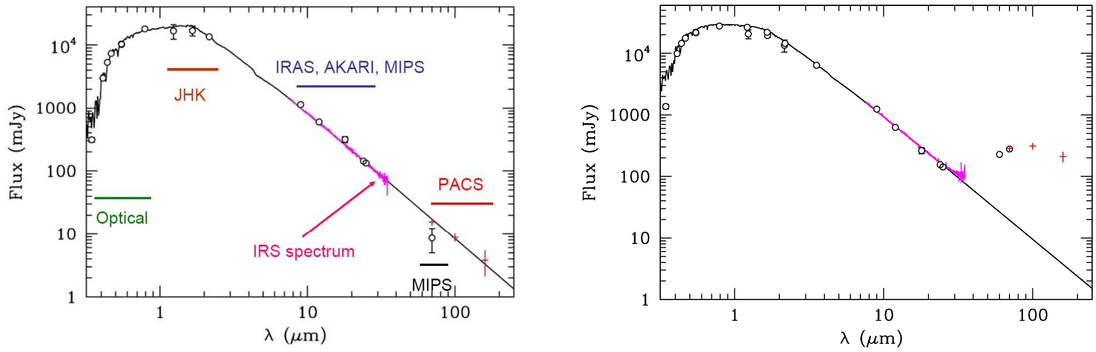

Figure 1: *Left:* Example of a star without excesses at any of the PACS wavelengths. Empty circles are optical, near- and mid-IR fluxes, namely $uvby{+}BVIJHK_s$ photometry, Akari 9 and 18 μm, colour corrected *IRAS* 12, 25 and 60 μm and *Spitzer*/MIPS 24 and 60 μm; in magenta the *Spitzer*/IRS spectrum is plotted. The black solid line is the photospheric fit normalized to the IRS spectrum. In red, the *Herschel*/PACS fluxes at 70, 100 and 160 μm with their corresponding uncertainties (statistical and systematic). *Right:* Example of a star with excesses at all PACS wavelengths.

Rayleigh-Jeans tail. In the pre-launch work, a very careful work of characterization of the stars was carried out. Optical and near-IR photometry and mid-IR observations were collected for all the sources. Also, the best stellar parameters were used to compute the photospheric SED. This provided us with a set of predictions of the photospheric fluxes at the *Herschel* wavelengths, which in turn were used to plan the observations.

Figure 1 (right) shows a typical SED of a star with excesses at all PACS wavelengths. A simple black-body fitting gives a temperature of about 55 K. Obviously, much more sophisticated modelling is being done on the stars of the sample, mainly on those cases where additional information is available; this would happen, for example, if the disc is resolved and some information of the spatial structure of the source can be extracted from the images. Figure 2 (left) shows an example of a source with a very small excess at 100 μm, a larger excess at 160 μm and no excess again at 250 μm. Intuitively, this hints towards a sort of ring-like belt with a dust temperature of about — or less than — 40 K.

3.2 Cold discs

A completely new result that has emerged from the DUNES observations is the fact that some SEDs show excesses at 160 μm and a pure or almost-pure photospheric behaviour at shorter wavelengths. Figure 2 (right) shows one of those cases. That kind of SEDs implies the presence of very faint ($L_{\rm dust}/L_{\odot} \sim 10^{-7} - 10^{-5}$) cold discs with $T_{\rm dust} \sim 20 - 25$ K (< 30 K). So far, it has been impossible to explain and model these discs within any known scenario. We are, most probably, facing a different physical regime, totally different when compared with that of the debris discs observed so far.

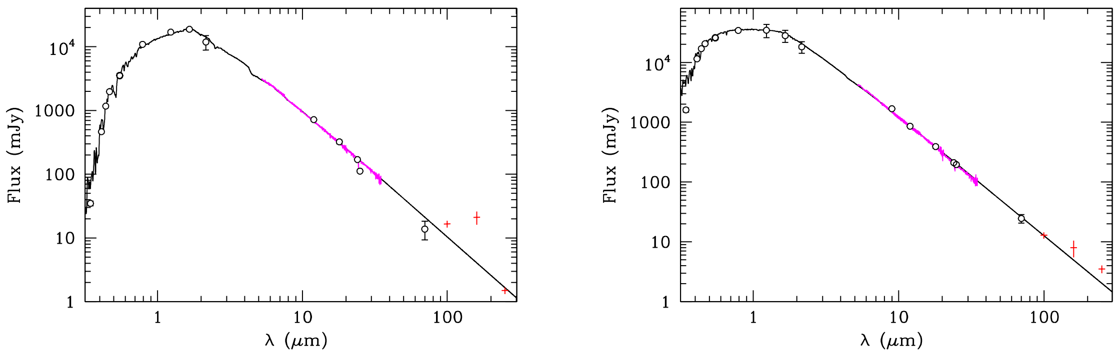

Figure 2: *Left:* Example of a star with a small excess at 100 μm a larger excess at 160 and almost no excess at 250 μm. *Right:* Example of a star with no excess at 100 μm and small excesses at 160 and 250 μm. This SED suggests the presence of a cold disc, with $T_{\rm dust} < 30$ K. The meaning of the symbols is as in Fig. 1.

3.3 A resolved disc around ζ^2 Ret

Figure 3 shows the scan-map PACS images of ζ^2 Ret (HIP 15371, G1 V, $d = 12$ pc, $L_{\rm bol} = 0.97\,L_\odot$, Age $\sim 2 - 3$ Gyr). 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 (100 μm), but the Eastern point-like peak is much fainter in the blue band (70 μm). 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.

Figure 4 shows the stellar SED as well as PACS fluxes from PS-E and the whole complex; the stellar photosphere is also plotted. The agreement between the observed 70 and 100 μm fluxes from the blue (70 μm) bright point-source and those predicted by the photospheric fit is excellent. This photometry and its positional alignment with the stellar position support our claim that the PACS blue point-like object is indeed ζ^2 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.

The source PS-E is a red object with a black body temperature T(70-100 μm) $\sim$ 40 K. We have pointed out that both PS-E and ζ^2 Ret are not resolved at 160 μm and that the flux peak at this wavelength is closer to PS-E. If we subtract from the measured 160 μm flux the stellar flux predicted for ζ^2 Ret and make the plausible assumption that the residual flux originates in PS-E, this 160 μm flux for PS-E is again consistent with a $\sim$40 K black body. PS-E 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-

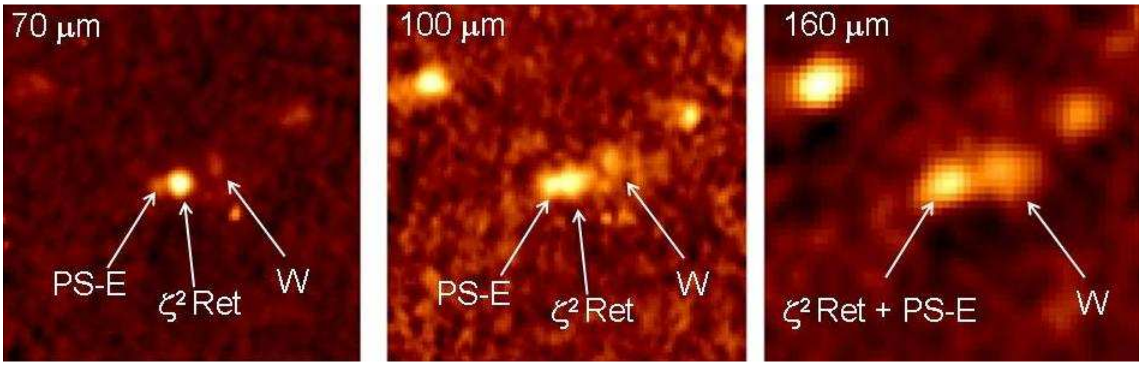

Figure 3: PACS images of ζ^2 Ret. Panels from left to right: 70 (blue), 100 (green) and 160 (red) μm. Field size is $100'' \times 100''$ with East to the left and North up.

South direction. In this case, the remaining flux corresponds to black body temperatures in the range ~30–40 K, and the total fractional luminosity from the entire structure surrounding ζ^2 Ret is $L_{\rm dust}/L_* \simeq 10^{-6}$.

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 ζ^2 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, disc-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 images as a dust ring surrounding ζ^2 Ret. We attribute the observed East-West asymmetry to a significant disc eccentricity $e \sim 0.3$. More details can be found in [4]. A more profound analysis and detailed modeling of ζ^2 Ret and the suggested Kuiper belt is deferred to a future paper.

4 Conclusions

Our results show the capabilities of *Herschel*/PACS and SPIRE to detect and resolve cold dust disks with a luminosity close to the solar Kuiper belt. This will allow us to deepen our understanding of planetary systems, in particular those associated with mature stars.

Acknowledgments

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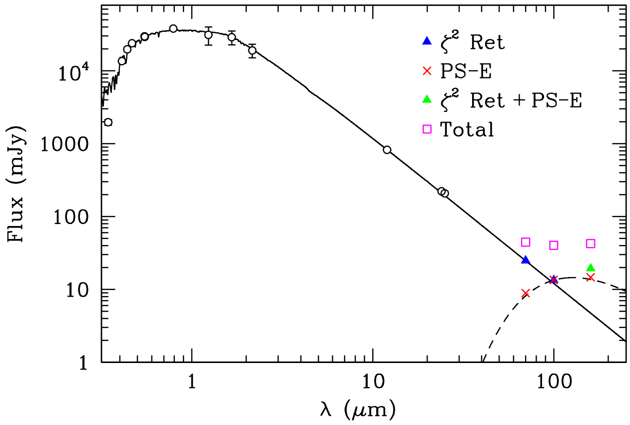

Figure 4: SED of ζ^2 Ret. Optical, 2MASS, *IRAS*, and *Spitzer* fluxes are indicated by black symbols. Blue triangles are ζ^2 Ret; red crosses are PS-E; green triangle is ζ^2 Ret+PS-E; magenta squares are total fluxes from the ζ^2 Ret complex. Error bars are smaller than the size of the symbols. The solid line is the best photospheric fit ($T_{\rm eff}$ = 5850 K, $\log g = 4.5$, and [Fe/H] = -0.23). The dashed line is a 40 K black body normalized at the PS-E 100 μm flux. The deduced 160 μm flux from PS-E is also plotted with a red cross.

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