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Debris disks as seen by Herschel: statistics and modeling

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Abstract

As leftovers of planet formation, debris disks represent an essential component of planetary systems. We first introduce the latest statistics obtained by the DUNES consortium, who are taking a census of extrasolar analogues to the Edgeworth-Kuiper Belt using the *Herschel* Space Observatory. Then we present a detailed study of the much younger debris disk surrounding the F5.5 star HD 181327. We derive strong constraints on the properties of its dust and we discuss its possible gaseous counterpart.

1. Introduction

To draw a complete picture of planetary systems as a whole, one needs to study all their constituents, from the largest gas giant planets to the smallest dust particles left behind after their formation, or reproduced by collisions. Herschel is an ESA space observatory with important participation from NASA. It provides far-infrared (IR) and sub-millimetre (mm) observations at an unprecedented spatial and spectral resolution and sensitivity [8, 9]. It features two Open Time Key Programmes that focus on the evolution of the dust grains and gas in circumstellar disks around young and Main Sequence stars, DUNES (DUst around nearby stars) and GASPS (GAS in Protoplanetary Systems).

2. DUNES statistics

DUNES aims at finding and characterizing faint extrasolar analogues to the Edgeworth-Kuiper Belt (EKB). We performed PACS (70, 100, 160 μm) and SPIRE (250, 350, 500 μm) photometric observations of cold disks around an unbiased, statistical sample of 133 nearby FGK Main Sequence (MS) stars (d < 25 pc), some known to host exoplanets. Results for the first 126 targets are presented in Tab. 1. The EKB sensitivity limit has been reached ($L_{\rm dust}/L_* \sim 10^{-7}$), revealing that ∼30% of nearby MS stars host a debris disk, which doubles the previous statistics. Most of the new detections were obtained for late-type stars, which were too faint for previous surveys. No clear tendency was found regarding the occurrence of planets versus the detection of excess, but the structure of two disks imply the presence of an exoplanet shaping the disk. A significant number of disks have been resolved with an unprecedented spatial resolution (see [2, 4, 5, 6]).

Table 1: DUNES statistics

Sp. type	F	G	K	Total
Sample	28	53	52	133
Observed	26	51	49	126
Non-excess	17	37	38	92
Excess (New)	9 (2)	14 (6)	11 (5)	34 (13)
"Peculiar"	2	2	4	
Resolved	4 (3)	8 (4)	4 (2)	12 (9)
Excess+planet	2 (2)	7 (1)	2 (1)	11 (4)

3. Detailed study of the debris disk surrounding HD 181327

Recently resolved images of the young Sun-like star HD 181327 (F5.5V, age ∼12 Myr) reveal an optically thin, belt of circumstellar material, presumed to result from collisions in a population of unseen planetesimals. The GASPS team obtained *Herschel*/PACS far-IR photometric observations of HD 181327 in the 3 PACS photometric bands (70, 100 and 160 μm). The disk is marginally resolved showing extended emission at 70 μm (Fig. 1). No gas was detected at the 3σ detection sensitivity from the [OI] 63 μm, [CII] 158 μm and [OI] 145 μm emission lines [7]. Together with newly reduced HST scattered light images, this new data provide the necessary measurements for an advanced analysis of the dust grains. In addition we were able to make some predictions on the gas content.

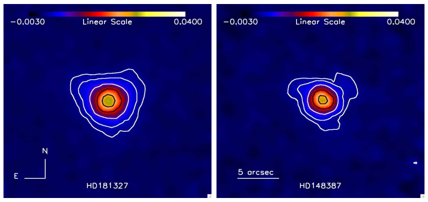

Figure 1: PACS 70 μm imaging of **(left)** HD 181327 and **(right)** a PSF reference star, HD 148387. (Field of view: 25"× 25"; brightness contours: 5, 10, 25, 50 and 75 times the background noise)

3.1. Modeling the dust continuum

We make a direct inversion of new HST/NICMOS scattered light brightness profile [10] to constrain the disk geometry. Knowledge of the disk radial density profile allows a detailed study of the dust grain properties: we use the GRaTer code [1] to compute a grid of models and we apply a Bayesian analysis to fit the dust Spectral Energy Distribution (SED) as to derive precise constraints on the grain size distribution and chemical composition. We show that simple grain compositions (icy silicates, porous silicates, etc.) fail at reproducing the observed SED from near-IR to sub-mm wavelengths. More sophisticated models are required to find an overall good fit to the observations (Fig. 2), with grains made of a mixture of silicates and organic material ($v_{\rm C} \sim 2v_{\rm Si}$), together with a large fraction of amorphous water ice (volume fraction of solid material $v_{\rm ice} = 0.67 \pm 0.07$) and a significant degree of porosity ($P = 63 \pm 21\%$). Assuming a single grain size distribution: ${\rm d}n(a) \propto a^{-\kappa}{\rm d}a$ for grains larger than $a_{\rm min}$ and smaller than $a_{\rm max} = 8$ mm (large enough to not impact the light emission properties), we find $a_{\rm min} = 0.81 \pm 0.31\mu$m and $\kappa = -3.41 \pm 0.09$, leading to a total mass $M_{\rm dust} = 0.051 \pm 0.016 M_\oplus$ (in grains with sizes up to to 1 mm). The overall results agree well with previously modelled debris disks such as β Pictoris, HD 141569A or HR 4796.

3.2. Gas modeling

The dust model was injected in the advanced thermo-chemical disk modeling code ProDiMo [11] to predict flux ratios in the OI, CII and CO (3-2) lines and derive a limit for the gas-to-dust (G/D) ratio in the disk, based on PACS upper limits. Assuming a high PAH abundance yields an upper limit on the gas mass $M_{\rm gas} \leq 17 M_\oplus$ but the non-detections of OI and CII do not provide unambiguous constraints. However, coupling with other tracers, e.g. CO lines, offers a hope to put much better limits on the low gas content of debris disks, with ALMA for instance.

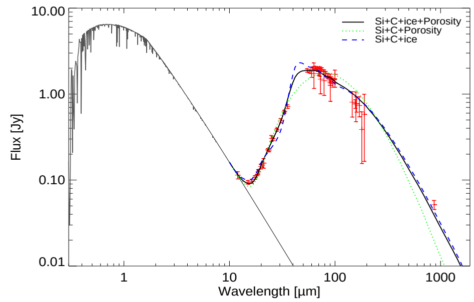

Figure 2: Best fit models for several 3- or 4-material mixtures. Red crosses: photometric data. Solid grey line: Synthetic stellar spectrum.

4. Conclusion

New *Herschel*/PACS continuum fluxes and HST images allowed a detailed analysis of the HD 181327 "debris belt". The grains surrounding the star are made of a mixture of silicates and carbonaceous material that is not only ice-rich, but needs to include a large degree of porosity to account for the thermal light spectrum of the disk. We note however that both the low albedo derived from scattered light images and the dust dynamics are not correctly explained by the use of spherical grains filled with vacuum, and that the grains are likely complex fluffy aggregates. We discuss the gas content of the debris disk based on *Herschel*/PACS non-detection lines. We highlight the need for the existence of a population of icy parent bodies to explain the survival of the icy grains surrounding the star.

The DUNES statistics offer on the other hand a broader view of the occurrence of debris disks about MS stars. A significant number of disks have been observed, bringing essential information to break the known degeneracies in the disk models. The unique performance of *Herschel* yielded the discovery of colder and fainter debris disks around nearby, in particular late-type, stars. Some of them are a challenge for current models in the framework of "classical" debris disk comprehension involving collisions of large planetesimals.

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