Debris disks around stars in the NIKA2 era

J.-F. Lestrade[1,*], *J.-C.* Augereau[2], *M.* Booth[4], *R.* Adam[6,9], *P.* Ade[7], *P.* André[10], *A.* Andrianasolo[2], *H.* Aussel[10], *A.* Beelen[11], *A.* Benoît[12], *A.* Bideaud[12], *O.* Bourrion[8], *M.* Calvo[12], *A.* Catalano[8], *B.* Comis[8], *M.* De Petris[13], *F.-X.* Désert[2], *S.* Doyle[7], *E. F. C.* Driessen[3], *A.* Gomez[15], *J.* Goupy[12], *W.* Holland[5], *F.* Kéruzoré[8], *C.* Kramer[14], *B.* Ladjelate[14], *G.* Lagache[16], *S.* Leclercq[3], *C.* Lefèvre[3], *J.F.* Macías-Pérez[8], *P.* Mauskopf[7,17], *F.* Mayet[8], *A.* Monfardini[12], *L.* Perotto[8], *G.* Pisano[7], *N.* Ponthieu[2], *V.* Revéret[10], *A.* Ritacco[14], *C.* Romero[3], *H.* Roussel[18], *F.* Ruppin[19], *K.* Schuster[3], *S.* Shu[3], *A.* Sievers[14], *P.* Thébault[20], *C.* Tucker[7], and *R.* Zylka[3]

[1] LERMA, Observatoire de Paris, PSL Research University,CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 75014 Paris, France

[2] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

[3] Institut de RadioAstronomie Millimétrique (IRAM), Grenoble, France

[4] Astrophysikalisches Institut und Universitätssternwarte, D-07745 Jena, Germany

[5] UK Astronomy Technology Centre, Royal Observatory, Edinburgh, UK

[6] LLR (Laboratoire Leprince-Ringuet), CNRS, École Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

[7] Astronomy Instrumentation Group, University of Cardiff, UK

[8] Univ. Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 53, avenue des Martyrs, 38000 Grenoble, France

[9] Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Plaza San Juan, 1, planta 2, E-44001, Teruel, Spain

[10] AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, 91191 Gif-sur-Yvette, France

[11] Institut d'Astrophysique Spatiale (IAS), CNRS and Université Paris Sud, Orsay, France

[12] Institut Néel, CNRS and Université Grenoble Alpes, France

[13] Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy

[14] Instituto de Radioastronomía Milimétrica (IRAM), Granada, Spain

[15] Centro de Astrobiología (CSIC-INTA), Torrejón de Ardoz, 28850 Madrid, Spain

[16] Aix Marseille Univ, CNRS, CNES, LAM (Laboratoire d'Astrophysique de Marseille), Marseille, France

[17] School of Earth and Space Exploration and Department of Physics, Arizona State University, Tempe, AZ 85287

[18] Institut d'Astrophysique de Paris, CNRS (UMR7095), 98 bis boulevard Arago, 75014 Paris, France

[19] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[20] LESIA, Observatoire de Paris, PSL Research University,CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 75014 Paris, France

Abstract. The new NIKA2 camera at the IRAM 30m radiotelescope was used to observe three known debris disks in order to constrain the SED of their dust emission in the millimeter wavelength domain. We have found that the spectral index between the two NIKA2 bands (1mm and 2mm) is consistent with the

*e-mail: jean-francois.lestrade@obpm.fr

Rayleigh-Jeans regime (λ^{-2}), unlike the steeper spectra (λ^{-3}) measured in the submillimeter-wavelength domain for two of the three disks − around the stars Vega and HD107146. We provide a succesful proof of concept to model this spectral inversion in using two populations of dust grains, those smaller and those larger than a grain radius a_0 of 0.5mm. This is obtained in breaking the slope of the size distribution and the functional form of the absorption coefficient of the standard model. The third disk − around the star HR8799 − does not exhibit this spectral inversion but is also the youngest.

1 Introduction

A debris disk orbiting a main sequence star is made of residual planetesimals left over from the agglomeration processes during the early phase of planet formation. It is akin to the asteroidal belt and the Kuiper Belt remaining from the planet formation in the solar system. The largest planetesimals − sub-km to hundreds of km in diameters − around other stars than the Sun have a total cross sectional area that is insufficient to be detected by our telescopes. However, when giant planets are present in these distant systems, planetesimals are gravitationally stirred and collide at a significant rate to produce a multitude of fragments including a myriad of small dust particles which has a total cross sectional area large enough to be observable for stars up to ∼ 100 pc. This dust can be detected both in scattered light and in thermal emission as an excess above the stellar photospheric level from mid-wave infrared to millimeter wavelengths or longer. This observable dust is a marker of a dynamically active planetesimal belt, indicating that the host star possesses a planetary system. The discovery of debris disks was one of the highlights of the first infrared satellite IRAS [1].

Dust emission in excess of photospheric emission can be used to constrain the size distribution of fragments as well as their composition [2, 3], and the dynamical state of the associated planetary system [4]. Theoretically, the equilibrium size distribution of fragments resulting from a collisional cascade is caracterised by the number density $n(a) \propto a^{2-3q_d}$ (a the fragment size) with $q_d = 11/6$ for the infinite self similar collisional model of asteroids and their debris in the solar system for material strength independant of size [5] and [6] [1]. However other size distributions are possible depending on the actual internal strength of the planetesimal material [7], and on the dynamical processes at work in the disk [4]. In addition, noticeably, the stellar radiation pressure blows the smallest grains out of the system and significantly perturbates the collisional cascade in imprinting a wavy pattern to the size distribution at small scale [8].

If micronic dust grains, abundant in this paradigm, absorb efficiently stellar radiation, they re-radiate inefficiently at long wavelengths. This increases their temperature and steepens the slope of the SED at long wavelengths. Constraining observationally the SED in this part of the spectrum is key to caracterise the type of collisional cascade at the root of the dust production in debris disks.

The SONS JCMT/SCUBA2 Legacy survey detected 48 debris disks in the submillimeter domain ($\lambda = 450\mu m$ and $850\mu m$) and found a large range of spectral slopes with $\beta \in [0-2.7]$ ($S_\nu \propto \lambda^{-(2+\beta)}$) [9, 10], which correspond to an index q_d possibly larger than 2 for the collisional cascade, *i.e.* size distribution steeper than the standard self similar collisinal model. However, with a sample of a dozen of debris disks observed by SMA and ALMA at 1.3mm and $850\mu m$, another group has found the range $q_d \in [1.61 - 1.88]$ [4], leading to an opposite

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[1]We recall that parameter q_d − the power law index of the general form for the number density of fragments per unit volume of space and per unit mass − is parameter α of eq. 2 in Dohnanyi's theoretical work[5]

Table 1. β measured by SONS, ALMA and NIKA2 (this work)

Star	age (Myr)	$\beta^{(1)}_{850/1100}$ (ALMA)	$\beta^{(2)}_{450/850}$ (SCUBA2)	$\beta_{1153/2000}$ (NIKA2)
Vega	400-600		0.9 ± 0.12	$\sim 0.0 \pm 0.32$
HD107146	80-200	0.61 ± 0.49	$0.8\text{-}1.0^{(*)}$	$\sim 0.0 \pm 0.18$
HR8799	20-50		1.7 ± 0.20	1.38 ± 0.45

(1) ALMA see [16] ; (2) SONS see [10] ; (*) based on grey body fit of β and λ_0 in [10].

conclusion for the size distribution. We have started NIKA2 observations during winter 2017 to complement these studies with photometry at 1.2mm and 2mm.

2 NIKA2 observations of three stars with known debris disks

The three stars HD107146, Vega and HR8799 were selected because their disks offered the largest flux densities at 2mm predicted in extrapolating from the SCUBA2 data in [10]. Observations of these three stars were conducted on October 29 and 30 2017 at the IRAM 30m radiotelescope at Pico de Veleta in Spain in fair weather conditions ($\tau_{225GHz} = 0.2 - 0.30$) using the new NIKA2 camera with its three arrays paved with Kinetic Inductance Detectors (KIDs) enclosed in a cryogenic system [11–13]. Arrays A1 and A3 providing the two linear polarisations at 1.2mm were combined to measure the flux density at this wavelength and array A2 was used to measure the total flux density at 2 mm. Uranus and MWC349 were used as primary and secondary calibrators to establish and check the flux density scale [14]. Data were calibrated and imaged using the NIKA2 data reduction pipeline. The flux densities were determined by fitting the standard gaussians at 1.2mm and 2mm as used to calibrate on Uranus in the pipeline [14].

Images of the three targets as well as their SED's with the two NIKA2 flux densities are plotted in Fig. 1. The final values of the NIKA2 flux densities and detailed comparison to the literature (*e.g.* [15, 16]) will be published elsewhere. HD107146 is unresolved within uncertainties (the main beam FWHMs are 11″ and 17.5″ at 1.2mm and 2mm, respectively). We shall carry a detailed comparison with the double ring structure found by ALMA for this disk [16]. Vega and HR8799 are slightly extended at the 30m/NIKA2. The North-West extension of the source HR8977 in Fig. 1 is also present in the SCUBA2 image at 850μm and ascribed to a background galaxy [10].

The spectral indices of the SED measured between 1153μm and 2000μm by NIKA2 are in Table 1 as well as values measured between 450μm and 850μm by SONS [10] for comparison. For two of the disks − around the stars Vega and HD107146 −, we have found that their NIKA2 spectral indices are consistent with the Rayleigh-Jeans regime (λ^{-2}), unlike their steeper spectra (λ^{-3}) measured at shorter wavelengths by SONS. It is interesting to notice that for HD107146 this spectral inversion is also supported by the flux density measured at $\lambda = 3.1$mm by the OVRO millimeter interferometer [17] and included in the SED of this star in Fig. 1. The third debris disk − around the star HR8799 − does not show this spectral inversion but is also the youngest in our small sample.

3 Proof of concept to model the spectral inversion

As a proof of concept we have developed a model to test whether or not a change in the spectral index is possible at all. First, we have modelled a narrow belt of spherical dust grains and used the standard size distribution $dN = N_0 a^{2-3q_d} da$ and the schematic absorption coefficient
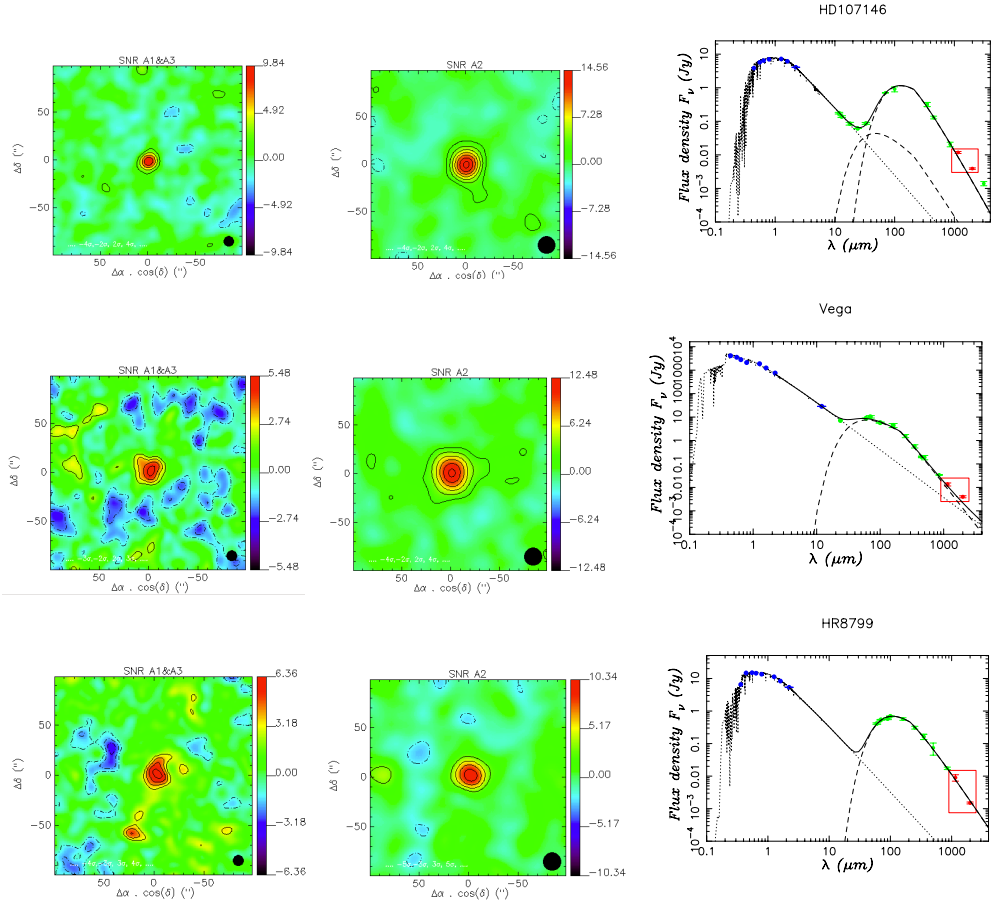
Figure 1. From top to bottom, NIKA2 SNR images of the G2V star HD107146 (age 80-200 Myr) at 28.5pc, the AOV star Vega (age 400-600 Myr) at 7.76 pc, and the A5V star HR8799 (age 20-50 Myr) at 39 pc (from top to bottom). Lower contours are $+2\sigma$ for HD107146 and Vega, and $+3\sigma$ for HR8799. See color scale for SNR. Beams are in black. **Left:** 1mm map (arrays A1 and A3 combined), **Middle:** 2mm map (array A2), **Right:** SED with the new NIKA2 photometric points at 260 GHz and 150 GHz in red and boxed. The SED of the disk emission has been fitted only to the photometric points at $\lambda < 1$mm ; it is apparent on the SEDs that HD107146 and Vega exhibit a spectral inversion beyond this wavelength while HR8799 does not. Blue dots are optical photometric data to which the NexGen photospheric model is fit. Green dots are the far IR to millimeter wavelength data. Red dots are NIKA2. A grey body emissivity is fit to the flux densities at $\lambda = 450\mu$m and $\lambda = 850\mu$m by eye for the dust ($\beta = 0.8$) and provides a reference model to show excesses at longer wavelengths for HD107146 and Vega. Dashed lines are the dust emission models, in the case of HD107146 a two narrow belt model is required to match both the mid IR and millimeter domains.

$Q_{abs}(a, \lambda) = 2a/\lambda$ when $2a < \lambda$ and $Q_{abs}(a, \lambda) = 1$ otherwise. Dust temperature was computed at thermal equilibrium, making the temperature of micronic-sized grains significantly larger than their black body temperature as it is well known. An example of such a SED is given in Fig. 2 (left) resulting in the spectral index $\alpha_{1153/2000} = -(2 + \beta) = -2.84$ between the two NIKA2 bands.

Then, we have sought to invert the spectral index from typically $\beta \sim 1$ in the submillimeter domain to $\beta \sim 0$ at $\lambda > 1$mm as observed for Vega and HD107146 with NIKA2. First, we broke the slope of the dust size distribution $(q_{d,1}, q_{d,2})$ at some grain radius a_0 varied over the range [0.1mm, 2mm] and in assuming continuity of the grain number densities at a_0 (*i.e.* $N_1 a_0^{2-3q_{d,1}} = N_2 a_0^{2-3q_{d,2}}$). This interval is where there is a major break in the grain size distribution when interaction between stellar radiation pressure and small grains at the bottom of the collisional cascade of planetesimals is accounted for [8] and [18]. In varying $q_{d,1}$ and $q_{d,2}$ from 1.7 to 2.0, we could not reproduce the observed spectral inversion with this model. So, we also forced a change in the schematic absorption coefficient described above in retaining a steep power-law $Q_{abs}(a, \lambda)$ for all grains of radii smaller than 0.5mm and in using $Q_{abs}(a, \lambda) = 1$ (black body) at all wavelengths for all larger grains. Although this abrupt change of the dust properties at some grain radius a_0 is not physically satisfactory and requires a smoother transition, it is interesting to note that it does yield a spectral inversion at $\lambda = 1$mm as seen in Fig. 2 (right). We note that in this model for HD107146, the temperature of micronic dust grains raises above 200 K producing the mid-infrared secondary peak seen in this figure. In our modeling, the fractional dust luminosity f_d has been kept constant, so the emitting areas of the two grain populations are redistributed in a way that makes the total emitting surface unchanged when $q_{d,1}$ and $q_{d,2}$ are varied.
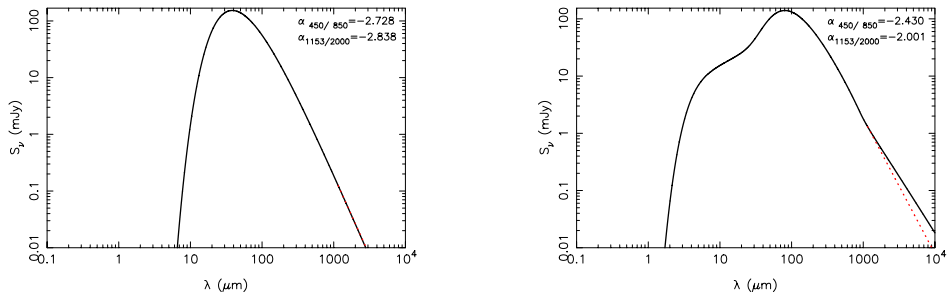

Figure 2. Proof of concept to test the possibility of a change in the spectral index at millimeter wavelengths in the SED of the debris disk around HD107146. **Left :** standard model using a single population of dust grains with the size distribution characterised by the index $q_d = 2$ and a shallow absorption coefficient (Q_{abs} power-law index is 1 here). This yields the spectral indices $\alpha_{450/850} = -2.73$ and $\alpha_{850/1153} = -2.84$, *i.e.* no spectral inversion is produced. **Right :** model using two populations of grains caracterised by a break in the grain size distribution ($q_{d,1} = 1.7$ and $q_{d,2} = 2.0$) and in the absorption coefficient (Q_{abs} power-law indices are 5 and 0.0 (black body)) for grains smaller and larger than $a_0 = 0.45$mm, respectively. This latter model does result in a spectral index inversion, changing from $\alpha_{450/850} = -2.43$ to $\alpha_{1153/2000} = -2.00$. The dotted red line extrapolates the grey body behavior found in the submillimeter domain into the millimeter domain for comparison with the modelled SED. The other parameters of the model are the dust fractional luminosity $f_d = 5 \ 10^{-3}$, minimum and maximum grain radii : 0.1μm and 10cm, stellar luminosity 1.1 $L_{\odot}$, stellar radius 1.09 $R_{\odot}$, disk radius 70AU, and star distance 28.5pc.

4 Concluding remarks

Further studies are planned to sophisticate the model in including a wavy form for the size distribution of the micronic grains as established on theoretical ground by [8] and in including

a more physical absorption coefficient based on the real dust properties of complex aggregates (shape, porosity, composition, etc) computable with the flexible software SIGMA [19]. We also plan to expand the NIKA2 observations to a larger sample of debris disks to investigate whether or not the black body behavior of dust in the millimeter domain found for Vega and HD107146 is a general property of debris disks, possibly with the exceptions of the youngest stars as already found for HR8799 in our small sample. In this case, the less evolved collisional cascade could possibly be less perturbed by stellar radiation pressure retaining a more abundant population of small grains as shown in [8]. A complete study is in progress and will be published.

Acknowledgements

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