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TAU CETI: OUR NEAREST COUSIN

E. Di Folco[1, 2], J. Péricaud[1,2], J.-C. Augereau[3] and J. Marshall[4]

Abstract. The 10 Gyr old G8V star τ Ceti is the closest Solar analogue. It harbors the less massive exo-Kuiper belt detected so far among debris disks stars. With a total disk mass only ten times larger than that of our Kuiper belt, it represents a case study of evolved debris disks. Whether its disk has been continuously eroded by steady-state collisions of planetesimals or recently regenerated by a dynamical instability remains a puzzling question. The detection of the dust points to the existence of (undetected) planetary bodies, which are expected to sculpt the belt and may scatter material inwards to the terrestrial planet region, where hot dust is also observed. Unfortunately, the disk morphology remains unknown. We report a recent Herschel PACS (70 μm and 160 μm)detection of a 15 au ring-like structure which is in conflict with the earlier SCUBA discovery. The disk is partly resolved by Herschel and we derive its morphology and the dust properties from the images and SED analysis with the GraTer modeling code. τ Ceti is a unique laboratory to highlight the long-term dynamical evolution of planetary systems and may represent an alternative outcome to the evolution of our Solar system.

Keywords: subject, verb, noun, apostrophe

1 Scientific background: the closest Kuiper belt analogue

Planetary systems around main-sequence stars can be indirectly revealed by the presence of massive belts of dust grains produced by collisions of planetesimals (see Wyatt 2008; Krivov 2010; Matthews et al. 2014, for recent reviews on debris disks). In our Solar system, the Edgeworth-Kuiper Belt (EKB) bears witness to the past dynamical history of our planetary system. The bulk of its mass ($\sim 0.12\,M_\oplus$) is located between 35 and 50 AU (Vitense et al. 2010, 2012, for detailed modeling). According to current models, it is believed to have been formed by the gravitational interaction of primordial planetesimals with the giant planets during a phase of outward migration (e.g., Morbidelli 2010, for an overview of the Nice model). Whilst up to recently all detected debris disks were much more massive than the EKB, Herschel sensitivity allows to investigate fainter systems that are more sibling to our Solar system.

τ Ceti, at a distance of 3.65 pc, is the nearest single solar-type star to the Sun. It is therefore a prime candidate for detailed imaging of mature planetary systems. Combining interferometric measurement of the stellar radius (Di Folco et al. 2004, 2007) with the asteroseismic estimate of the density, Teixeira et al. (2009) inferred a stellar mass $M_\star = 0.78 \pm 0.01\,\mathrm{M}_\odot$. Di Folco et al. (2004) also derived an age of 10.0 ± 0.5 Gyr for this G8V dwarf which thus appears to be older than the Sun, and as such to host the oldest resolved debris disk around a main-sequence star. Whether its massive belt is a remnant of the primordial debris disk or has been recently regenerated remains a puzzling enigma.

First detected with IRAS (Backman et al. 1986), and ISO (Habing et al. 2001) at 60 and 170 μm, its cold dust belt ($T \sim 60$ K) was first imaged at 850 μm by Greaves et al. (2004). The disk emission was marginally resolved by SCUBA on JCMT, suggesting a very inclined structure at a position angle $PA = 6°$ with an outer edge of 55 AU. The total flux density (5.8 ± 0.6 mJy, of which 1.1 mJy comes from the star) corresponds to a sub-mm grain mass of $5.10^{-4}\,\mathrm{M}_\oplus$, which is extrapolated to $M_{\mathrm{disk}} = 1.2\,\mathrm{M}_\oplus$ by assuming a collisional cascade with parent bodies as large as 50 km and an age of 10 Gyr. This mass is an order of magnitude larger than that

[1] Univ. Bordeaux, Laboratoire d'Astrophysique de Bordeaux, UMR 5804, F-33270, Floirac, France
[2] CNRS, LAB, UMR 5804, F-33270 Floirac, France
[3] UJF-Grenoble 1/CNRS-INSU, Institut de Planétologie et d'Astrophysique de Grenoble UMR 5274, F-38041, Grenoble, France
[4] Depto. de Fisica Teorica, universidad Autonoma de Madrid, Cantoblanco, 28049, Spain

of today's Kuiper Belt ($\sim 0.12\,M_{\oplus}$, e.g., Vitense et al. 2010), whereas it is the less massive belt imaged so far among debris disks. The decline of disks fractional excess, and hence of mass, with age could be explained by steady-state processing (Löhne et al. 2008), although a possible delayed stirring (Wyatt 2008) cannot be ruled out .

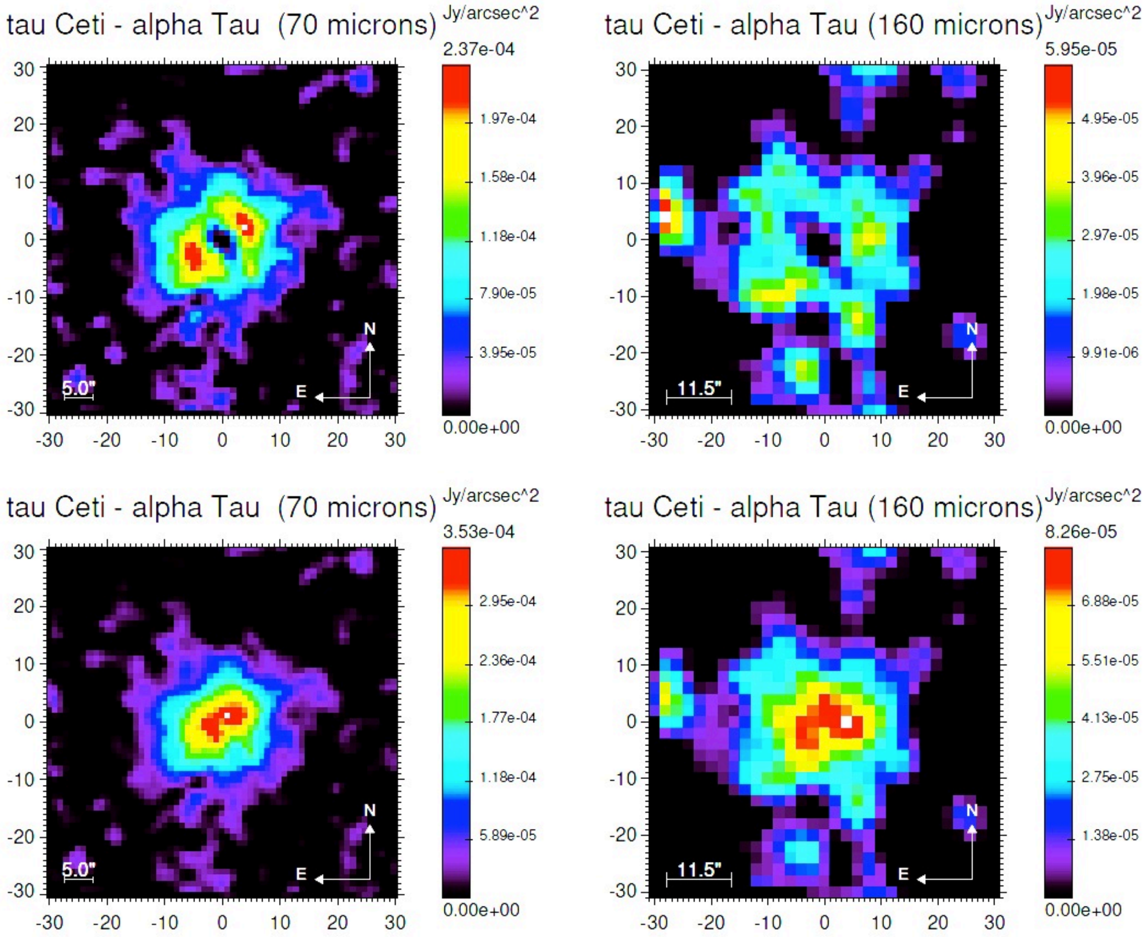

Fig. 1. Herschel-PACS images of the debris disk around τ Ceti at $70\,\mu$m (left) and $160\,\mu$m (right). **Top panels:** the PSF observed on a reference (point-like) star has been subtracted to the reduced image of τ Ceti after normalizing the PSF at the maximum of the image surface brightness: it highlights the resolved disk emission. **Bottom:** same image subtraction process but the reference image is normalized at the expected photospheric flux of τ Ceti: it highlights the contribution of the disk alone to the total emission.

2 Herschel-PACS detection

We collected archival Herschel data from the PACS and SPIRE instruments. Aperture photometry is calculated in a 20" radius circle and confirms a significant IR excess longward of$\lambda = 70\,\mu$m. The disk flux excess is detected up to $350\,\mu$m, it can be fitted with a modified black-body at a temperature of about 85 K, which corresponds to grains at a typical distance of about 10 au around this G8V star. We also analyzed the PACS images at 70 and $160\,\mu$m. We used the reference star α Tau to estimate the point spread function (PSF), this star was observed with the same scanning mode of the PACS instrument. In Fig.1, we display the PSF-subtracted images in order to enhance the resolved emission beyond the contribution of the unresolved photosphere of τ Ceti. This is done as follows: we subtract the image of the reference star after normalizing the latter at the maximum value of the surface brightness in the τ Ceti image, this leaves a null value at the center of the image with two wings that reveal the extended emission that is due to the debris disk emission. in this process, part of the disk emission is also subtracted. We thus propose a second set of PSF-subtracted images, where we normalize the PSF surface brightness at the expected photospheric level of τ Ceti (modeling the stellar SED with a Nextgen model that fits the short wavelength flux density). In this way, only the photospheric emission is subtracted and the image is supposed to trace the disk emission. The PSF width is estimated to about 6" at 70 μm and 12" at 160 μm. The resolved emission is prominent at 70 μm, and less significant at 160 μm. It is detected out to about 50 au in the 70 μm image, the disk emission appears to be inclined with a position angle $PA = 135 \pm 10$ deg. We also estimate a disk inclination of 40 ± 3 deg by fitting the image isophots with elliptical lines. We note that the image is significantly different from the detection reported with the SCUBA instrument by Greaves et al. (2004). The Herschel detection shows a moderately inclined system oriented in a direction that is orthogonal to the resolved emission claimed by the latter authors. We also report no major azimutal brightness asymmetry in the far-IR images.

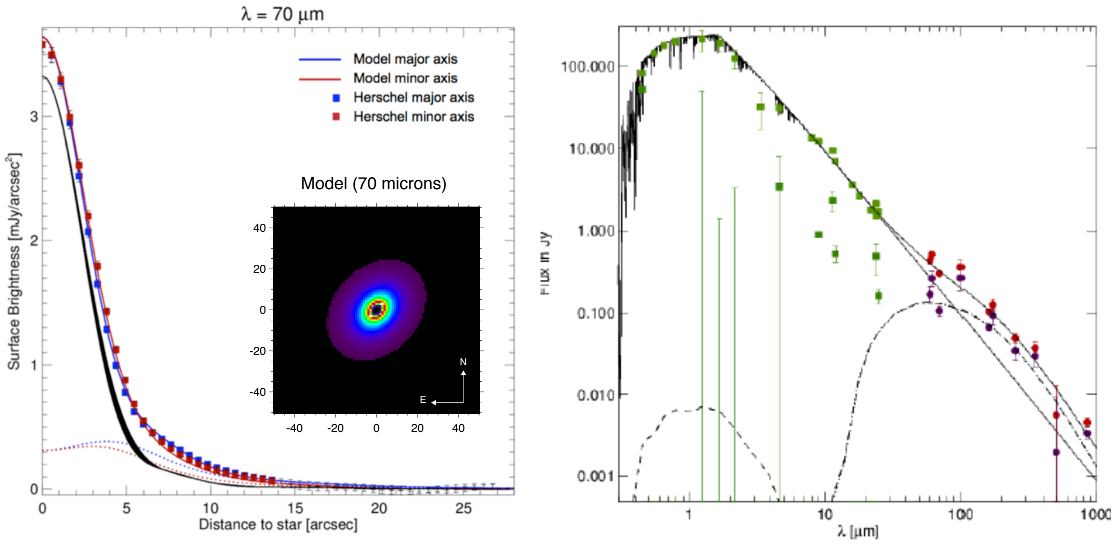

Fig. 2. Left: PACS Image profiles at 70 μm along the minor and major axis (dots) compared to the best-fit model estimates (colored solid lines). The best model emission is illustrated in the inset. **Right:** Spectral energy distribution for the star and the disk (solid line is the best Nextgen model, red dots are the photometric values taken into account n the fit), and for the disk alone (purple markers for the Herschel + SCUBA measurements, dashed and dash-dotted lines for the best-fit model).

3 Disk modeling with GraTer

We used the GraTer code (e.g., Lebreton et al. 2012) to constrain the physical parameters of the debris disk using the simultaneous constraints of the disk SED and the resolved images. only the 70 μm image was taken into account as it provides the most significant detection. The SED and the image profiles are fitted simultaneously. We assume for the dust grains distribution a ring-like structure, peaking at radius R_0, with adjustable inner and outer slopes. The grains size distribution index (κ), the minimum grain size ($s_{\rm min}$) and the total mass ($M_{\rm d}$) are free parameters. We fixe the outer radius of the disk at 100 au, and consider only pure silicate grains. About 10^6 models have been computed, a Bayesian analysis yields the probability density functions for the fitted parameters, which allows us to estimate robust uncertainties. We find that the ring of grains partly resolved in the Herschel images peaks at 15 ± 1 au, with an outer slope of $\alpha = -1.3 \pm 0.2$. The size distribution index is consistent with what is expected from a typical collisional cascade $\kappa = -3.42 \pm 0.02$, and the minimum grain size is found to be very small ($\sim 10^{-2}\,\mu$m). The result of the fitting procedure can be found in Fig.2, where our model of dust emission at 70 μm is also illustrated. These result are consistent with the preliminary analysis recently proposed by Lawler et al. (2014). The the stirring mechanism that ensures the production of dust in such an old system is not yet understood. The disk luminosity is clearly too large to be the result of a long-term steady-state collisional cascade lasting for 7–10 Gyr, following Wyatt (2008). The total dust mass is one order of magnitude larger than in our present-day EKB. A delayed stirring must be invoked, with multiple possible physical causes (recent collision, planet or planet migration-induced mechanism, late-heavy bombardment-like event...).

4 Conclusions

We have analyzed the far-IR images of the old debris-disc surrounding the nearby solar-type star τ Ceti. The partially resolved emission allow us to constrain, through a detailed modeling of the thermal dust grain emission, the main characteristics of the dust ring. Our results suggest that the grains are arranged in a ring-like structure with a radial extension comparable to that of the Edgeworth-Kuiper belt in our solar system. τ Ceti is a remarkable system because its disk of cold debris is about one order of magnitude more massive than our EKB, while the system appears to be much older than ours. Our modeling yields for the cold dust belt typical characteristics of collision dominated structures. The origin of the dynamical stirring for a 10 Gyr old system remains to be found. Detailed imaging at higher spatial resolution with ALMA should help characterizing the parent bodies of the observed grains in the far-IR domain. It should also solve the surprising discrepancy between the far-IR and the sub-mm emission morphology.

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