The Disk and Planets of Solar Analogue τ Ceti

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Abstract. τ Ceti is a nearby, mature star very similar to our Sun, with a massive Kuiper belt analogue (Greaves et al. 2004) and possible multiplanet system (Tuomi et al. 2013) that has been compared to our Solar System. We present infrared and submillimeter observations of the debris disk from the *Herschel Space Observatory* and the James Clerk Maxwell Telescope (JCMT). We find the best model of the disk is a wide annulus ranging from 5-55 AU, inclined from face-on by 30°. Tuomi et al. (2013) report five possible super-Earths tightly nestled inside 1.4 AU, and we model this planetary system and place dynamical constraints on the inner edge of the disk. We find that due to the low masses and fairly circular orbits of the planets, the disk could reach as close to the star as 1.5 AU, with some stable orbits even possible between the two outermost planets. The photometric modelling cannot rule out a disk inner edge as close to the star as 1 AU, though 5-10 AU produces a better fit to the data. Dynamical modelling shows that the 5 planet system is stable with the addition of a Saturn-mass planet on an orbit outside 5 AU, where the Tuomi et al. analysis would not have detected a planet of this mass.

1. Introduction

τ Ceti is the closest G star (3.65 pc) that hosts both a debris disk and exoplanet candidates. Greaves et al. (2004) found a moderately resolved disk around the mature star using JCMT-SCUBA at 850 μm, and Tuomi et al. (2013) report a possible system of five super-Earths.

2. *Herschel* Data

Herschel observations were obtained as part of the Guaranteed Time Key Programme "Stellar Disk Evolution."

The disk is resolved at 70 μm and 160 μm, and marginally resolved at 250 μm (Figure .1).

2.1 Disk Model

To measure the properties of the disk, a model is built using simple blackbody dust grains (following method of Kennedy et al. 2012, 2013). The modelled disk is azimuthally symmetric with a power-law surface density distribution, and the parameters are varied until the convolved image matches the *Herschel* images within uncertainties (Figure .2).

A second technique is also used based on fitting the measured fluxes in each band. This SED-based model uses realistic dust grains (following Wyatt & Dent 2002) with a collisional size distribution. We find that no grain model exists that can match both *Herschel* and submillimeter SCUBA-2 data with a single annulus, hinting at a cooler, separate disk component to explain SCUBA and SCUBA-2 observations (Greaves et al. in prep.)

Table .1: Disk Properties Derived from Modelling

	Best-fit	Uncertainty
Disk inclination	35° from face-on	±10°
Inner disk edge	3 AU	-2, +7 AU
Outer disk edge	55 AU	±10 AU
Min. grain size	15 μm	±8 μm
Surface density profile	Flat	Linearly rising also works

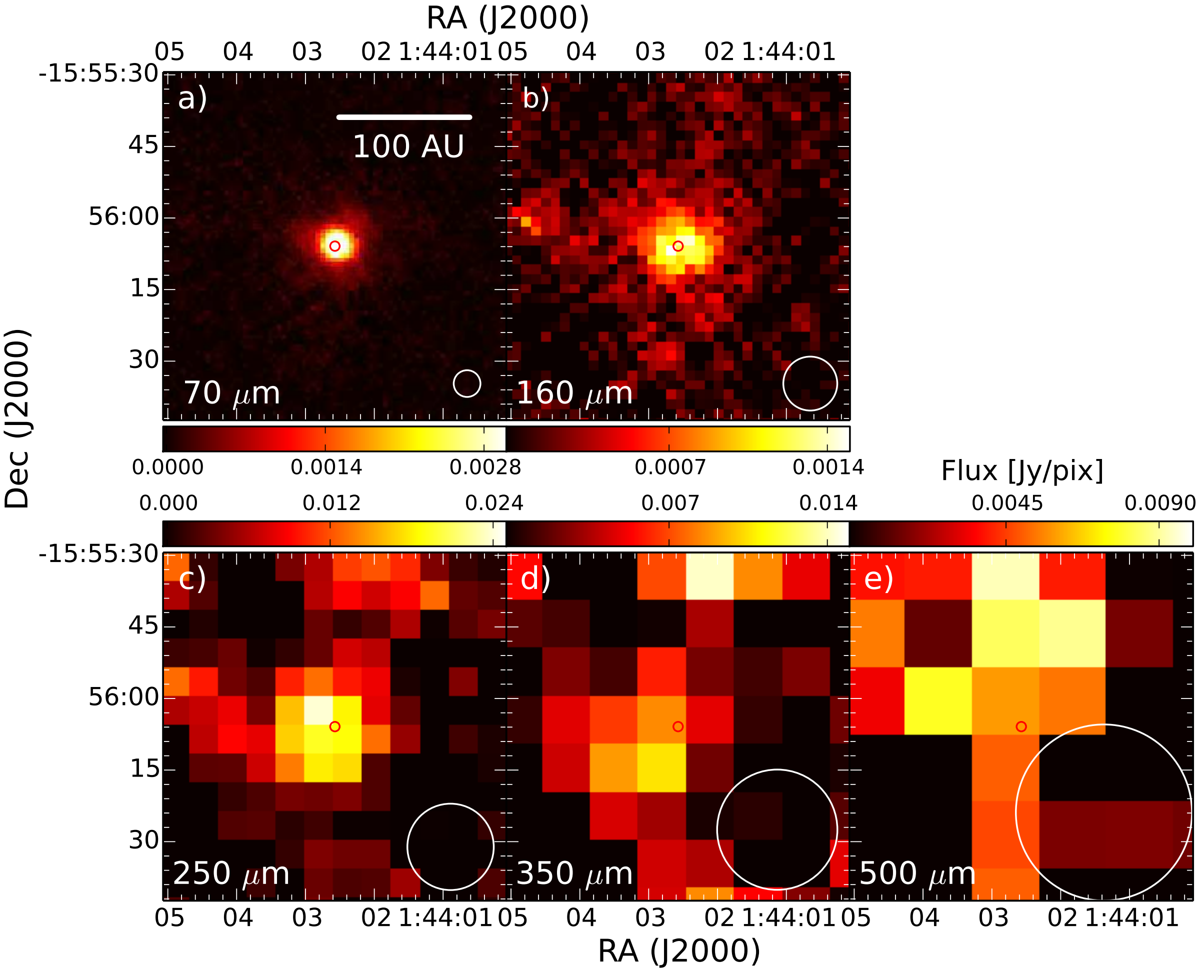

Figure .1: Cropped *Herschel* maps of τ Ceti centered on the position of peak 70 μm emission (shown in each panel as a small red circle). Beam size at each wavelength is shown for reference in each panel (larger white circles). A scalebar showing the color range of flux in Jy per pixel is shown above each sub-figure. a) 70 μm emission, b) 160 μm emission, c) 250 μm emission, d) 350 μm emission, and e) 500 μm emission. A bar in a) shows the spatial extent of 100 AU at the distance of τ Ceti.

3. Possible Planetary System

Our dynamical simulations show the multiplanet system proposed by Tuomi et al. (2013) is stable down to nearly face-on (large planetary masses), with moderate (Tuomi's best-fit) eccentricities. However, the largest eccentricities allowed by Tuomi et al.'s Bayesian analysis of the RV data are not stable. Using the best fit inclination from the disk (~30°), planet masses ($M \sin i$) from Tuomi et al. should be doubled, resulting in planetary masses from 4-13 $M_{\oplus}$.

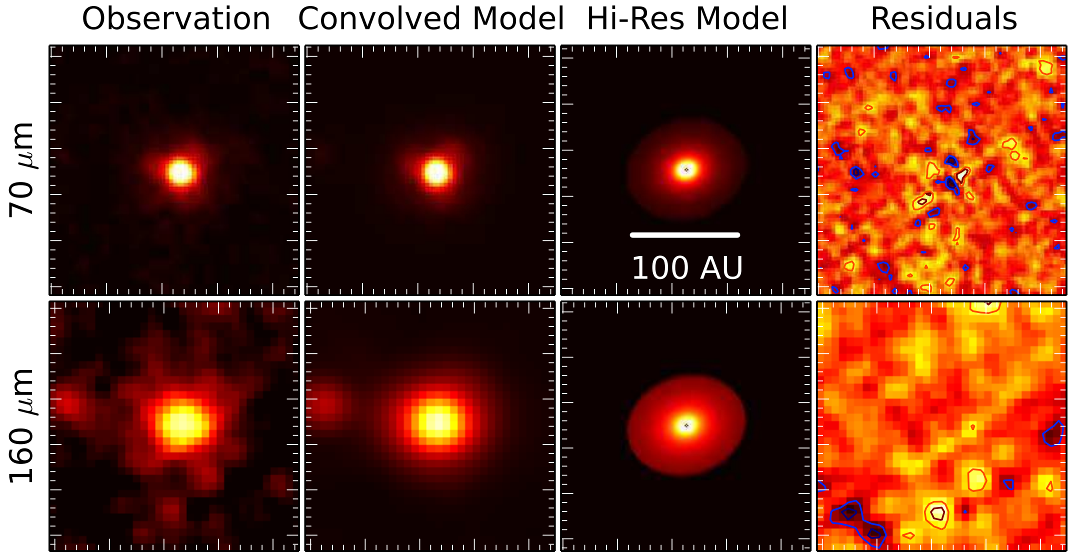

Figure .2: An example of a disk model that matches the *Herschel* images. Panels are on the same scale as Figure .1, and a 100 AU scale bar is shown for reference. Top panels show the *Herschel* data and model at 70 μm, lower panels at 160 μm. From left to right, panels show the *Herschel* data, the model convolved to the same resolution as the data, a high resolution version of the model, and the residuals of data-model.

Extending the Tuomi et al. analysis, we can rule out Neptune- and larger mass planets in the system inside 5 AU. Saturn- and slightly smaller mass planets could exist at 5-10 AU. Though the inner part of this solar system may be populated by rocky planets, there is not a Jupiter-analogue inside 10 AU in the system.

Low planet masses and fairly circular orbits mean that the planets do not clear large annuli. Stable disk particle orbits are possible to within 0.1 AU of the outermost planet, and even between the outermost two planets.

The best-fit inner disk edge required by the *Herschel* data is consistent with the presence of the planetary system. However, higher resolution data is required to make sure the disk does not overlap with the predicted orbits of the planetary system. Soon-to-be-acquired ALMA data will help to resolve this.

4. Summary and Conclusions

Wyatt et al. (2012) find that there are two broad categories of planetary systems: those with one or more >Jupiter mass planets which are unlikely to host debris disks, and those with planets <Saturn mass, which are likely to host debris disks. τ Ceti appears to fall nicely into the second category. *Herschel* data reveal that the disk is ∼30° from face-on, and extends to 55 AU from the star. The best-fit inner edge is 2-3 AU, which is consistent with dynamical limits from the possible multiplanet system. But the resolution of *Herschel* cannot rule out

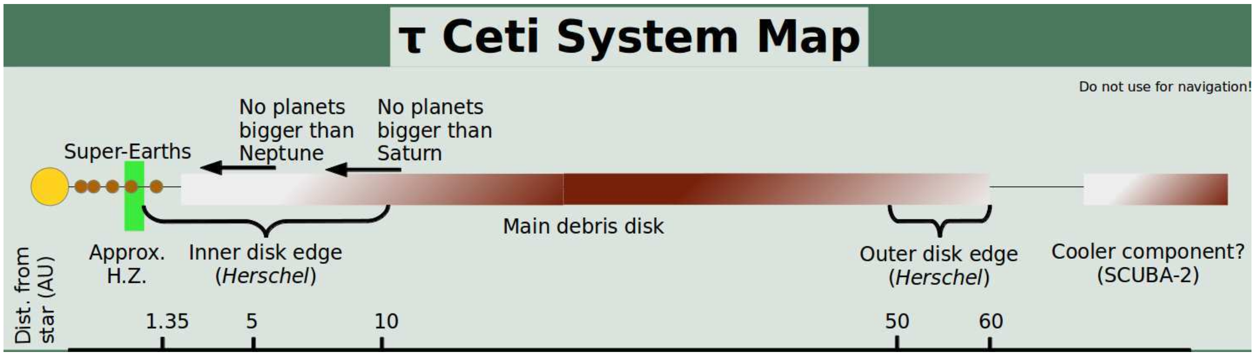

Figure .3: A rough map of the τ Ceti system based on this work.

an inner edge as close to the star as 1 AU, which overlaps with the orbit of the outermost planet. ALMA cycle 2 data will resolve the inner edge, and help clarify the existence of the proposed planetary system.

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