Herschel-PACS observation of the 10 Myr old T Tauri disk TW Hya. Constraining the disk gas mass

W F. Thi  
*University of Edinburgh*

G Mathews  
*University of Hawaii*

F Menard  
*Laboratoire d'Astrophysique de Grenoble*

P Woitke  
*UK Astronomy Technology Centre*

G Meeus  
*UAM Campus Cantoblanco*

*See next page for additional authors*

Follow this and additional works at: [https://tigerprints.clemson.edu/physastro_pubs](https://tigerprints.clemson.edu/physastro_pubs)  
Part of the [Astrophysics and Astronomy Commons](https://tigerprints.clemson.edu/physastro_pubs)

**Recommended Citation**  
Please use publisher's recommended citation.
Herschel-PACS observation of the 10 Myr old T Tauri disk TW Hya
Constraining the disk gas mass


(Affiliations can be found after the references)
Received 31 March 2010; accepted 28 April 2010

ABSTRACT

Plants are formed in disks around young stars. With an age of ~10 Myr, TW Hya is one of the nearest T Tauri stars that is still surrounded by a relatively massive disk. In addition a large number of molecules has been found in the TW Hya disk, making TW Hya the perfect test case in a large survey of disks with Herschel–PACS to directly study their gaseous component. We aim to constrain the gas and dust mass of the circumstellar disk around TW Hya. We observed the fine-structure lines of [O I] and [C II] as part of the Open-time large program GASPS. We complement this with continuum data and ground-based CO (sub)millimeter lines to derive the gas and dust masses. We detect the [OI] line at 63 μm. The other lines that were observed, [O I] at 145 μm and [C II] at 157 μm, are not detected. No extended emission has been found. Preliminary modeling of the photometric and line data assuming [12CO]/[13CO]=69 suggests a dust mass for grains with radius <1 mm of ~1.9 × 10^{-4} M⊙ (total solid mass of 3 × 10^{-3} M⊙) and a gas mass of (0.5–5) × 10^{-3} M⊙. The gas-to-dust mass may be lower than the standard interstellar value of 100.

Key words. Circumstellar disks

1. Introduction

Plants are formed in the disks that surround a large fraction of T Tauri stars. Knowledge of the gas mass available at different disk ages is essential to constrain giant planet formation models. Most studies estimate the dust mass from millimeter continuum emission and assume the gas mass is a factor of 100 times larger. This conversion factor has been calibrated for the interstellar medium but is likely not valid for disks, especially those that are evolving toward debris disks or where most of the gas has accreted onto the planetary atmosphere. Disk gas mass estimates derived from observations of 12CO and optically thinner 13CO emission are at least a factor of 10 lower than the mass derived from dust observations assuming the interstellar medium conversion factor. The discrepancy has been ascribed to CO photodissociation at disk atmosphere and freeze-out onto cold dust grains in the disk midplane (e.g., Qi et al. 2004; Thi et al. 2001). An alternative explanation is that the CO abundance is not different and the gas in disks has been depleted.

The PACS instrument (Poelchau & al. 2010) on-board the Herschel Space Telescope (Pilbratt & al. 2010) makes it possible to observe lines from species that result from the photodissociation of CO (atomic oxygen and singly ionized carbon). With observations of all the major gas-phase carbon and oxygen-bearing species, we can more precisely constrain the disk gas mass.

At a distance of ~56 pc (Wichmann et al. 1998), TW Hya is one of the nearest classical T Tauri stars with an estimated age of 10 Myr (Barrado Y Navascués 2006). Its proximity allows us to attain an order of magnitude higher mass sensitivity than objects in the Taurus molecular cloud. Fits to the spectral energy distribution (SED) provide an estimate of the gas disk mass of 6 × 10^{-2} M⊙ after applying a conversion factor of ~75 (Calvet et al. 2002). This large disk mass at this advanced age is surprising as the median disk lifetime is only 2-3 Myr (Haisch et al. 2001). TW Hya is considered a transition object with an optically thin inner cavity and an optically thick outer disk (Calvet et al. 2002; Ratzka et al. 2007). The fit to the SED also suggests that grains have grown to at least ~1 cm.

The star TW Hya was observed as a Science Demonstration Project object and is part of the Herschel-GASPS program (Dent & GASPS team 2010). Herschel observations of the disk around the Herbig Ae star HD169142 are presented by Meeus et al. (2010). In this letter we use fine-structure lines in addition to continuum data and CO (sub)millimeter lines to directly constrain the gas mass and compare it to the dust mass derived from fits to the SED.
We obtained photometry in the “blue” (70 µm) and “red” (160 µm) band of the PACS camera by doing mini scan maps with a scan speed of 20′′ and a scan length of 2′ (obsid 1342187342). The total duration of this map was 731 sec, with an on-source time of 146 seconds. The results are 3.90 ± 0.14 Jy and 7.38 ± 0.04 in the blue and red band respectively and have an absolute accuracy estimated to be 5% for the blue channel and 10% for the red channel. These values agree very well with the observed IRAS flux densities and also with the continuum flux densities measured with the PACS spectrometer (Table 1). We also used the PACS spectrometer to target the [OI] line at 63 µm in line scan mode, and the [OI] and [CII] lines at 145 and 158 µm, respectively in range scan mode (obsid 1342187127 PacsLineSpec and obsid 1342187238 PacsRangeSpec). Only the [OI] line at 63 µm was detected and we report upper limits for the other two lines; see Table 1. The absolute accuracy of PACS spectroscopy is currently estimated to be about 40%, but is expected to improve in the future. Figure 1 shows the spectrum centered at the position of the OI line at 63 µm of the central pixel.

2. Observations and results

We first augmented the Herschel photometric data with continuum measurements from the literature. We also retrieved and reduced archival SCUBA data for TW Hya obtained during two nights with very good sub-millimeter transmission ($F_\nu$(450 µm) = 4.25 ± 0.85 Jy and $F_\nu$(850 µm) = 1.38 ± 0.14 Jy). The disk around TW Hya has an internal cavity from up to 4 AU where the gas and dust density are very low. Most of the mass is located in the external ring. The inner ($R_{\text{in}}$) and outer radius ($R_{\text{out}}$) of the external ring are well constrained by imaging studies and are fixed at 4 AU and 200 AU respectively [Roberge et al. 2005; Qi et al. 2004; Hughes et al. 2007]. We fitted the SED with the 3D Monte-Carlo radiative transfer code MCFOST [Pinte et al. 2004]. We chose to restrict to a parametric disk model for this letter. The disk has a radial density profile with index $\epsilon$. The flaring is characterized by an opening angle $H_0$ at a given radius $R_0$ and a flaring index $\gamma$ so that the gas scale-height is given by $H = H_0 (R/R_0)^\gamma$. The low continuum flux in the 30–100 µm region suggests that the outer disk flaring is weak. Amorphous olivine grains were used [Dorschner et al. 1995] with a power-law size-distribution defined by a minimum radius $a_{\text{min}}$, maximum radius $a_{\text{max}}$, and power-law index $p$. The dust size-distribution and mass are well constrained by the continuum emission at long wavelengths. The fit to the long-wavelength photometric points including the new Herschel-PACS data is shown in Fig. 2 and the disk parameters constrained by the fit are listed in Table 2. The inferred dust mass in grains with radius < 1 mm is $M_{\text{dust}} = 1.9 \times 10^{-4} M_\odot$ and the total mass in solids (pebbles) up to $a_{\text{max}} = 10$ cm is $M_{\text{solid}} = 3 \times 10^{-3} M_\odot$. However, the fit fails to account for the flux at ~25 µm, which may stem from our assumption of a unique temperature for grains of all sizes. The flux around 20-30 µm is strongly inclination-dependent because we adopted...
a sharp density change between the inner cavity and the outer ring at 4 AU. Solids as large as 10 cm in radius are needed to account for the observed 7 mm and 3.6 cm flux (Wilner et al. 2000). The small grains in the TW Hya disk account for 6% of the total solid mass. We also estimated a mass in small grains at radii beyond a few AU. In panels a and b we can see that the density, dust and gas temperature structures (Thi et al. 2004). Following the characterization of the disk structure from the SED, we ran three series of models with the thermo-chemical code ProDiMo (a detailed description is given in Worke et al. 2009). In ProDiMo species abundances are computed at steady-state from the gas, and dust temperature as well as the local UV field for the photodissociation reactions. A constant isotopologue ratio [13CO]/[12CO] of 69 is assumed. The gas kinetic temperature is computed by balancing heating and cooling processes. Line profiles are computed by non-LTE radiative transfer within ProDiMo. The disk is assumed to be passively heated. The disk turbulent velocity and inclination are well constrained by millimeter interferometric data (Qi et al. 2004). The outer disk is irradiated by direct and scattered stellar photons as well as by interstellar UV photons. The free parameters of the gas simulations are the disk gas mass $M_{\text{gas}}$ (between $3 \times 10^{-4}$ and $0.3 M_\odot$), the fraction of polycyclic aromatic hydrocarbons (PAHs) in the disk with respect to the interstellar abundance $f_{\text{PAH}}$, and the cosmic ray flux $\zeta = (1.7 \times 10^{-17}$ s$^{-1}$ in the ISM). Observations show that PAHs are depleted by at least a factor of 10 ($f_{\text{PAH}} = 0.1$) in disks with respect to the interstellar abundance (Geers et al. 2006). Because the gas is mostly heated by photoelectrons ejected from PAH, the PAH abundance is the main free parameter that controls the gas temperature. The three series of models correspond to three possible states: disks with a very low PAH abundance ($f_{\text{PAH}} = 0.01$), disks with a typical PAH abundance ($f_{\text{PAH}} = 0.1$), and X-ray irradiated disks with a low PAH abundance ($f_{\text{PAH}} = 0.01$) but ten times the standard cosmic ray flux ($\zeta = 1.7 \times 10^{-17}$ s$^{-1}$) to mimic the influence of strong X-ray emission (Bruderer et al. 2009). The model results are plotted in Fig. 3. The density, dust and gas temperature structure are shown for a typical disk in the appendix. The results from series 3 are within 10% of the values of series 2, suggesting that X-ray does not influence the line fluxes that are emitted at radii beyond a few AU. In panels a and b we can see that the OI 63 $\mu$m and 145 $\mu$m flux increases with the disk gas mass. The OI 63 $\mu$m line is optically thick while the OI 145 $\mu$m line is optically thin for all models. Both lines arise mostly in a ring at 4 AU. Solids as large as 10 cm in radius are needed to account for the observed 7 mm and 3.6 cm flux (Wilner et al. 2000). The small grains in the TW Hya disk account for 6% of the total solid mass. We also estimated a mass in small grains at radii beyond a few AU.

Fig. 2. Fit to the SED generated by ProDiMo using the parameters from MCFOST. The input Phoenix stellar spectrum plotted in red is from Brett & Hauschildt (2005). IUE (UV) data are from Valenti et al. (2003). The 2MASS J, H, K, IRAS, and Spitzer-MIPS photometry are archival data. The Spitzer-IRS spectrum is published by Ratzka et al. (2003). The Herschel-PACS data are fitted in filled green triangles. The average $UBVRI$ photometric points are published by Racinski & Krautter (1983). The 800 $\mu$m and 1.1 mm data points (inverted filled blue triangles) are taken from Weintraub et al. (1989). The 3.4 mm point (open blue square) is from Wilner et al. (2003). The 7 mm and 3.6 cm points (filled blue square) are from Wilner et al. (2000).
We estimate the gas mass to be \((0.5–5) \times 10^{-5} M_\odot\) and \(5 \times 10^{-3} M_\odot\). Fig. 3. Three series of model results compared to observations. The blue boxes enclose the model outputs for disk gas mass between \(5 \times 10^{-4} M_\odot\) and \(5 \times 10^{-3} M_\odot\). Panel a shows the predictions and observation of the OI 63 \(\mu\)m line. The 3\(\sigma\) uncertainty range is plotted as dashed lines. Panel b and c show the predicted fluxes and the 3\(\sigma\) upper limits for the OI 145 \(\mu\)m and CII lines. The two lower panels (d and e) are the comparison between observations and model outputs for \(^{12}\)CO 3-2 emission and the \(^{12}\)CO/\(^{13}\)CO 3-2 ratio. Panel f shows the normalized cumulative fluxes for a \(10^{-3} M_\odot\) model (series 1). The diamonds (\(\sigma R_{\text{out}}=174\) AU model, \(\sigma R_{\text{out}}=120\) AU model) show the predictions for TW Hya from GH08.

### 4. Conclusion

The Herschel-PACS spectral observations were used to constrain the gas disk mass surrounding the 10 Myr T Tauri star TW Hya. We estimate the gas mass to be \((0.5–5) \times 10^{-3} M_\odot\) compared to the dust mass \((\sigma_{\text{dust}} < 1\) mm\) of \(1.9 \times 10^{-4} M_\odot\). The gas-to-dust mass ratio is \(\sim 2.6–26\), lower than the standard interstellar value of 100. The ratio gas-to-total-mass in solids is \(\sim 0.17–1.7\). Although the disk is still massive, a significant fraction of the primordial gas has already disappeared. A large fraction of the primordial gas may have been evaporated due to the strong X-ray flux from TW Hya. TW Hya is the first example where the disk gas mass around a transitional T Tauri star can be determined accurately and directly from gas phase lines. However, more detailed modeling that includes X-ray physics and \(^{13}\)CO photochemistry is needed to confirm the low gas mass.

### References

Mejia, G., Pinte, C., Montesinos, B., & GASPS team. 2010, A&A
Pilbratt, G. & al. 2010, A&A
Poglitsch & al. 2010, A&A

Appendix A: Density and temperature structure

We show in Fig. A.1, A.2, and A.3 the density, dust temperature, and gas temperature profile respectively for a disk model with $M_{\text{gas}}=2.9 \times 10^{-3} M_{\odot}$, $f_{\text{PAH}}=0.1$, and $\zeta=1.7 \times 10^{-17}$ s$^{-1}$. All other parameters are given in Table 2.

![Density profile](image)

**Fig. A.1. Density profile**.
Fig. A.2. Dust temperature profile.

Fig. A.3. Gas temperature profile. The contour of $A_V=1$ is shown in white.