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LETTER TO THE EDITOR

Gas in the protoplanetary disc of HD 169142: Herschel’s view*


(Affiliations are available in the online edition)

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ABSTRACT

In an effort to simultaneously study the gas and dust components of the disc surrounding the young Herbig Ae star HD 169142, we present far-IR observations obtained with the PACS instrument onboard the Herschel Space Observatory. This work is part of the open time key program GASPS, which is aimed at studying the evolution of protoplanetary discs. To constrain the gas properties in the outer disc, we observed the star at several key gas-lines, including [OI] 63.2 and 145.5 μm, [CII] 157.7 μm, CO 72.8 and 90.2 μm, and o-H2O 78.7 and 179.5 μm. We only detect the [OI] 63.2 μm line in our spectra, and derive upper limits for the other lines. We complement our data set with PACS photometry and 12CO data obtained with the Submillimeter Array. Furthermore, we derive accurate stellar parameters from optical spectra and UV to mm photometry. We model the dust continuum with the 3D radiative transfer code MCFOST and use this model as an input to analyse the gas lines with the thermochemical code ProDiMo. Our dataset is consistent with a simple model in which the gas and dust are well-mixed in a disc with a continuous structure between 20 and 200 AU, but this is not a unique solution. Our modelling effort allows us to constrain the gas-to-dust mass ratio as well as the relative abundance of the PAHs in the disc by simultaneously fitting the lines of several species that originate in different regions. Our results are inconsistent with a gas-poor disc with a large UV excess; a gas mass of 5.0 ± 2.0 × 10−3 M⊙ is still present in this disc, in agreement with earlier CO observations.

Key words. planetary systems – circumstellar matter – stars: pre-main sequence – protoplanetary disks – infrared: planetary systems

1. Introduction

Giant gas–planets form in protoplanetary discs within the first 10 Myr after protostar formation. Therefore the amount of gas that is present in a disc at a given time is very important, as it determines whether these planets can still be formed. The study of the dust is equally important, as it witnesses the first steps of planet formation. A lot is known about the dust in protoplanetary discs thanks to the Space Observatories ISO and Spitzer: different degrees of dust processing were observed with no clear relation to stellar properties, while grain growth could be related to the disc structure (e.g. Sicilia-Aguilar et al. 2007; Meeus et al. 2009). Gas is more difficult to observe, as the spectral lines are not very strong. Most gas studies are based on CO lines in the near-IR (warm gas) or in the mm, where CO freeze-out onto grains is a complicating factor (e.g. Brittain et al. 2007; Dent et al. 2005). However, as gas lines are stronger in the far-IR, we expect this field to experience major breakthroughs in the coming years based on data obtained with the Herschel Space Observatory (Pilbratt et al. 2010), which provides sensitive far-IR photometry and spectroscopy.

The source HD 169142 is a young – age 6×106 Myr (Grady et al. 2007) – Herbig Ae star with an IR to millimetre excess attributed to a circumstellar (CS) disc. Submillimeter Array (SMA) observations show a disc in Keplerian rotation with radius r = 235 AU and inclination i = 13° (Raman et al. 2006) and a total gas mass of 0.6–3.0 × 10−2 M⊙ (Panić et al. 2008). For a Herbig Ae, the star is unusual as it has a small near-IR excess (e.g. Dominik et al. 2003). Furthermore, SWS/ISO spectra revealed that the silicate 10 μm feature, detected in the majority of the Herbig Ae/Be stars (only 8 out of 53 lack the feature, Juhász et al. 2010) is lacking in HD 169142 (Meeus et al. 2001). This absence can be explained if the silicate grains are either too large or too cold to emit at 10 μm (Meeus et al. 2002). On the other hand, features of polycyclic aromatic hydrocarbons (PAHs), which can be excited by UV photons, were clearly detected with ISO and Spitzer. Based on the near to far-IR ratio, Grady et al. (2007) suggested that the inner region has already cleared some material, and that the inner and outer disc are not coupled. However, this might also be explained by a reduced opacity due to grain growth.

In this paper we show the first Herschel observations of HD 169142, and use radiative transfer and chemical models to constrain the gas properties of the outer disc.

2. Herschel PACS observations

Our observations are part of the Herschel open time key program GASPS (P.I. Dent, see Mathews & Thi 2010; and...
70 μm and 11″ at 160 μm. We derived photometry using an aperture of 21″, and applied an aperture correction from the PACS PhotChopNod Release Note (Feb. 22, 2010). This gives a flux of 27.35 ± 0.03 Jy at 70 μm and 17.39 ± 0.05 Jy at 160 μm, with a flux calibration uncertainty of 5% in the blue, and 10% in the red. Applying the flux uncertainty of 40% for the spectroscopy, our photometry is consistent with the continuum fluxes measured from the spectral scans. Given the smaller error in the photometry, however, we give preference to those fluxes, and expect to reduce the spectroscopic flux uncertainties in the future.

3. Determination of stellar parameters
Because previous studies list conflicting effective temperatures, we re-estimated the fundamental parameters. Photometry excluding the contribution from the cool companion (at a distance of 9′3; Grady et al. 2007) was collected from Cutri et al. (2003), Zacharias et al. (2004) and Sylvester et al. (1996). We also analysed optical spectra, taken with CES/CAT with a resolution of ∼60,000. Temperatures were selected by simultaneously fitting the lines from neutral and singly ionised species. The synthetic stellar spectra were computed using the ATLAS9 and SYNTHY codes by Kurucz (1993). χ² tests show that models between T eff = 7500 K, log g s = 4.0, [Fe/H] < −0.50 and T eff = 7800 K, log g s = 4.1, [Fe/H] = −0.25 match our data.

Furthermore, the IUE obtained five spectra of HD 169142: one between 1200–1900 Å (SW) and four between 1900–3200 Å (LW). The SW spectrum is unusable for measurements below 1650 Å, but suggests emission lines of OI (1304 Å), CII (1335 Å) and CIV (1650 Å), but suggests emission lines of OI (1304 Å), CII (1335 Å) and CIV (1550 Å) – unfortunately, most are dominated by bad pixels. The LW spectra do not show any variability (over a period of 4.5 months), match the stellar photosphere, and do not show emission features. Overall, the IUE data (obtained from the INES INTA archive) do not give evidence for a UV excess.

4. Analysis
4.1. Dust and continuum modelling
Far-IR lines emerging from a CS disc are affected by the stellar UV irradiation, disc mass and geometry, dust size and composition, as well as PAH abundance. In order to interpret the lines observed with Herschel, it is crucial to first obtain a solid knowledge of the disc structure in the disc, based on as many observations as possible, like SED, scattered light images and visibilities. Each of these observations provide complementary views of the disc structure and the dust properties. The disc model is calculated with the Monte Carlo radiative transfer code MCFOST (Pinte et al. 2006, 2009), as outlined below.

We consider an axisymmetric, slightly flared density structure with a Gaussian vertical profile, assuming power-laws for the surface density and scale height. We assume homogeneous and spherical dust grains (Mie theory), with sizes distributed according to the power-law f(\(\alpha\)) ∝ \(\alpha^{-3.5}\) between \(a_{\text{min}}\) and \(a_{\text{max}}\), where \(\alpha\) is the grain radius. The dust is assumed to be well-mixed with the gas, i.e. the dust/gas ratio is constant throughout the disc. The star is reproduced by a uniformly radiating sphere with previously determined parameters \(T_{\text{eff}} = 7800\) K, \(\log g_s = 4.1\), [Fe/H] = −0.25, and \(R_{\ast} = 1.6 R_\odot\). Parameters are adjusted to simultaneously fit the SED, the Spitzer/IRS spectrum (Sloan et al. 2005), the 1.1 μm HST image (Grady et al. 2007) and the 1.3 mm SMA visibilities (Panić et al. 2008). The scattered light image mainly constrains the flaring index to a low value (around 1.0) and the mm visibilities indicate a surface density varying as \(r^{-1}\).
Because we lack simultaneous visible and near-IR photometry, the temperature is too high (2400 K) for dust, even carbon, to survive. Light and thermal emission from the inner and outer disc, respectively.

The blue dot-dashed and pink dashed lines are the contributions (scattered light and thermal emission) from the inner and outer disc, respectively. The green line represents the best MCFOST model, in red the atmosphere model. The derived from the spectroscopic observations (red crosses). The green line indicates (Draine et al. 2003) and 30% amorphous carbon (ACAR 1 cm). The weak emission around 10 m can be reproduced with a low PAH abundance due to the low continuum emission in that region. We modelled the PAHs that apart from the uncertainties in the observations, systematic uncertainties in the physical description of various chemical and radiative processes in the models render a proper gas mass determination difficult. The observational uncertainty in the 13CO line flux – which appears to be a dominant gas mass determination – is 13% (model #1). For the standard ratio gas/dust = 100, we found model #2, which fits the [O I] 63.2 m and 12CO line fluxes, but the 13CO line is slightly too high (2.5 sigma). A better fit is obtained with gas/dust = 33 (model #3), which simultaneously fits all three detected lines, and agrees with all other line upper limits. However, we emphasise that apart from the uncertainties in the observations, systematic uncertainties in the physical description of various chemical and radiative processes in the models render a proper gas mass determination difficult. The observational uncertainty in the 13CO line flux – which appears to be a dominant gas mass tracer – translates to a ratio range gas/dust = 22 to 50. An increase of the [O I] 63.2 m flux by 40% (to account for the calibration uncertainty and match the photometry) would indicate a higher gas temperature. In our modelling, this is best interpreted by a larger PAH abundance ($f_{PAH} = 0.02$), as the other more relevant parameter, $f_{UV}$, is constrained by the non-detection of the [CII] 157.7 m line.

The spatial distribution of the $^{12}/^{13}$CO molecules predicted by our chemical model is consistent with the interferometric line of sight.
observations by Panić et al. (2008). Figure 3 shows a detailed analysis of the spatial origin of the various emission lines, as derived from model #3. The [OI] 63.2 μm and 145.5 μm lines originate from a radial disc region extending from the beginning of the outer disc at 20 AU to about 75 AU and 60 AU, respectively. Both lines are optically thick (τ_{line} ≈ 10−100) and come from relative heights z/r ≈ 0.2−0.3. The [CII] 157.7 μm line is optically thin and extraordinarily weak in this model, due to the lack of stellar UV photons <110 nm that are capable of ionising carbon (f_{UV} ≈ 0). The 12CO and 13CO J = 2 → 1 lines probe the conditions in the outermost disc regions 43−185 AU and 52−190 AU, respectively, and are extremely optically thick (τ_{line} ≈ 100−5000). Whereas the 12CO line comes from the PDR-like CO surface z/r ≈ 0.4, the more transparent 13CO line probes slightly deeper layers z/r ≈ 0.2. These findings are quite stable and robust among all calculated models.

5. Conclusion

We presented the first PACS observations of HD 169142 and showed the unique capability of Herschel to obtain an independent gas mass determination by simultaneously modelling the atomic fine-structure lines that are temperature sensitive (due to their high excitation energies), when combined with ground-based observations of 12/13CO-lines. We showed that the observations are consistent with a simple model of a disc hosting a gap, with a continuous structure between 20 and 200 AU in which the gas and dust are well-mixed, but stress that this solution is not unique. We determined the location of the emitting species, and constrained the gas/dust ratio to be ~22−50. We also derived that the UV excess emission, if present, must be lower than f_{UV} = 0.005. We derive a gas mass between 3.0 and 7.0 X 10^{-3} M_{⊙}, in agreement with the gas mass determination based on the CO lines alone (Panić et al. 2008). Despite indications that the HD 169142 disc is transitional, it is still a gas-rich disc. Furthermore, although there is dusty material close to the central star, the UV excess indeed due to accretion is extremely weak, if at all present. We will apply a similar modelling strategy for future GASPS observations, with the aim to study gas dissipation in a wide range of protoplanetary discs.

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