Mon. Not. R. Astron. Soc. **365,** 1283–1287 (2006) doi:10.1111/j.1365-2966.2005.09825.x

The circumstellar disc around the Herbig AeBe star HD169142

W. R. F. Dent,[1] J. M. Torrelles,[2*†] M. Osorio,[3] N. Calvet[4] and G. Anglada[3]

[1] *UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ*
[2] *Instituto de Ciencias del Espacio (CSIC)-IEEC, C/Gran Capità, 2-4, 08034 Barcelona, Spain*
[3] *Instituto de Astrofísica de Andalucía (CSIC), Apdo. Postal 3004, 18080 Granada, Spain*
[4] *Department of Astronomy, University of Michigan, 825 Dennison Building, 500 Church Street, Ann Arbor, MI 48109, USA*

Accepted 2005 October 31. Received 2005 October 18; in original form 2005 August 22

ABSTRACT

We present 7 mm and 3.5 cm wavelength continuum observations towards the Herbig AeBe star HD169142 performed with the Very Large Array (VLA) with an angular resolution of $\simeq$1 arcsec. We find that this object exhibits strong ($\simeq$4.4 mJy), unresolved ($\lesssim$1 arcsec) 7 mm continuum emission, being one of the brightest isolated Herbig AeBe stars ever detected with the VLA at this wavelength. No emission is detected at 3.5 cm continuum, with a 3σ upper limit of $\simeq$0.08 mJy. From these values, we obtain a spectral index $\alpha \gtrsim 2.5$ in the 3.5 cm to 7 mm wavelength range, indicating that the observed flux density at 7 mm is most likely dominated by thermal dust emission coming from a circumstellar disc. We use available photometric data from the literature to model the spectral energy distribution (SED) of this object from radio to near-ultraviolet frequencies. The observed SED can be understood in terms of an irradiated accretion disc with low mass accretion rate, $\dot{M}_{\rm acc} \simeq 10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$, surrounding a star with an age of $\simeq$10 Myr. We infer that the mass of the disc is $\simeq$0.04 M$_{\odot}$, and is populated by dust grains that have grown to a maximum size of 1 mm everywhere, consistent with the lack of silicate 10 μm emission. These features, as well as indications of settling in the wall at the dust destruction radius, led us to speculate that the disc of HD169142 is in an advanced stage of dust evolution, particularly in its inner regions.

Key words: circumstellar matter – stars: individual: HD169142 – planetary systems: protoplanetary discs.

1 INTRODUCTION

Herbig Ae/Be (HAeBe) stars are young stellar objects (YSOs) of intermediate mass, characterized by large infrared (IR) excesses due to the presence of circumstellar discs, and are believed to be the more massive analogues of T Tauri stars (Herbig 1960; Strom et al. 1972). The presence of discs around isolated HAeBe stars has been mainly inferred by modelling their spectral energy distribution (SED) at millimetre, submillimetre, IR and optical wavelengths (e.g. Dullemond, Dominik & Natta 2001; Natta et al. 2001, 2004; Meeus et al. 2001; Dominik et al. 2003; Dullemond & Dominik 2004; Acke, van den Ancker & Dullemond 2005; Hernández et al. 2005). However, only a few of these dust/gas structures have been (marginally) spatially resolved [sizes $\leqslant$2 $\times$ beam; e.g. Mannings & Sargent (1997)].

As a continuation of a survey programme to study the circumstellar dust/gas around isolated HAeBe stars (including submillimetre wavelength CO observations) performed by Dent, Greaves & Coulson (2005), we have searched at the Very Large Array (VLA) archive for centimetre/millimetre wavelength continuum observations towards those stars where submillimetre CO emission was detected. The main goal of that search was to identify dust disc candidates which may be resolvable through future high angular resolution continuum observations. By reducing and analysing the available VLA archive data on these sources, we have found in particular that the HAeBe star HD169142 is associated with strong 7-mm continuum emission (data presented in this paper).

The A5Ve star HD169142 is a relatively nearby (d = 145 pc) example of an isolated HAeBe star (Dunkin, Barlow & Ryan 1997; van den Ancker 1999; Meeus et al. 2001). It has significant far-IR emission as well as a mid-IR excess (Malfait, Bogaert & Waelkens 1998), and is one of the brightest such objects at submillimetre wavelengths (Sylvester et al. 1996). The absence of large-scale nebulosity or extended molecular gas in the region suggests no nearby on-going star formation and that HD169142 is a relatively evolved HAeBe star. HD169142 also shows a bright and narrow submillimetre emission CO line (Greaves, Mannings & Holland 2000; Dent et al. 2005), as well as a narrow optical O I line profile (Acke et al. 2005). These results indicate that any circumstellar disc around the star must be close to face-on, with an inclination angle of

*E-mail: jmt@roe.ac.uk
†On sabbatical leave at the UK Astronomy Technology Centre, Royal Observatory Edinburgh.

Table 1. Summary of the VLA observations of HD169142.

λ (cm)	Date	Array configuration	Phase calibrator Name	$F_\nu{}^a$ (Jy)	Beam[b] Size (arcsec)	PA	rms[b] (μJy beam^{-1})	HD169142 $F_\nu{}^c$ (mJy)
0.7	2002 Sep 22–23	CnB	18210−25282	0.6	0.9 × 0.4	−35°	300	4.4
3.5	2005 May 15	B	1911−201	2.4	1.7 × 0.7	+8°	25	$\lesssim 0.08^d$

[a]Bootstrapped flux density of the phase calibrator.
[b]For natural weight maps.
[c]Flux density of the source.
[d]3σ upper limit.

≃10° (Dent et al. 2005). Attempts to resolve the continuum emission have resulted in an upper limit to the mid-IR disc radius of 150 au (Jayawardhana et al. 2001), although there is evidence of polarized near-IR emission extending to ≃200 au (Kuhn, Potter & Parise 2001). An unpublished Submillimetre Common-User Bolometer Array (SCUBA) map from the James Clerk Maxwell Telescope (JCMT) archive shows unresolved emission at 850 and 450 μm, with a deconvolved upper limit to the size of ≃4 arcsec (FWHM) (or a radius of ≃300 au) in the dust continuum at 450 μm. Finally, observations of the 3.3 μm feature of polycyclic aromatic hydrocarbons (PAHs) show that this emission arises from an extended region, with a size of ≃0.3 arcsec or 43 au (Habart, Natta & Krugel 2004).

In this paper, we present 3.5 cm and 7 mm continuum observations carried out with the VLA towards the source HD169142. In Section 2.1, we discuss the nature of its continuum emission at centimetre/millimetre wavelengths. In addition to the VLA data, in Section 2.2 we compile data from the literature to construct the SED of HD169142 over a wide range of wavelengths, from radio to near-ultraviolet. In Section 3, we compare the SED with a grid of self-consistent irradiated accretion disc models from D'Alessio et al. (2005). Our studies imply that a disc with mass $\simeq 0.04\,\mathrm{M}_\odot$ and a population of grains grown to a maximum radius of ≃1 mm surrounding a star with an age of 10 Myr can reasonably explain the main characteristics of the observed SED.

2 OBSERVATIONS

2.1 VLA observations and results

The 3.5 cm and 7 mm wavelength continuum observations were carried out with the VLA of the National Radio Astronomy Observatory (NRAO)[1] in the B (2005 May 15) and CnB (2002 September 22–23) configurations, respectively. For both wavelengths, a bandwidth of 100 MHz and two circular polarizations were used. All data were reduced with the Astronomical Image Processing System (AIPS) of NRAO using standard VLA procedures. The absolute amplitude calibrator was 3C 286, with assumed flux densities of 5.2 Jy ($\lambda = 3.5$ cm) and 1.5 Jy ($\lambda = 7$ mm), while the phase calibrators were 1911−201 (for the $\lambda = 3.5$ cm observations, with a bootstrapped flux density of 2.4 Jy) and 18210−25282 (for the $\lambda = 7$ mm observations, with a bootstrapped flux density of 0.6 Jy). Cleaned maps were made by Fourier transforming the (u, v) data with natural weighting. The resulting synthesized beam sizes and rms sensitivities of the maps were ≃1.7 × 0.7 arcsec [position angle (PA) = 8°] and ≃25 μJy beam^{-1} at 3.5 cm wavelength, and ≃0.9 × 0.4 arcsec (PA = −35°) and ≃300 μJy beam^{-1} at 7 mm wavelength, respectively (Table 1).

A bright (≃4.4 mJy beam^{-1}), unresolved (≲1 arcsec) 7 mm continuum source is detected towards HD169142 (see Fig. 1), with its peak position at α(J2000) = 18$^{\mathrm{h}}$24$^{\mathrm{m}}$29$^{\mathrm{s}}$.78, δ(J2000) = −29°46′49″.4 (±0″.1), coinciding with the optical position of the star (Hog et al. 1998). To our knowledge, this is one of the brightest 7 mm continuum sources ever detected with the VLA towards a HAeBe star (from the literature we see that only HD163296, with a flux density of 6 mJy at 7 mm, is brighter; Natta et al. 2004).

No 3.5 cm continuum emission is detected towards HD169142, with an upper limit of ≃0.08 mJy beam^{-1} (3σ level). From these values, we obtain a spectral index $\alpha \gtrsim 2.5$ ($F_\nu \propto \nu^\alpha$) in the 3.5 cm to 7 mm wavelength range. This high value of the spectral index indicates that free–free emission cannot account for the observed flux density at 7 mm, and that thermal dust emission from a circumstellar disc is most likely the main contribution to the observed flux density at this wavelength (see also Section 3).

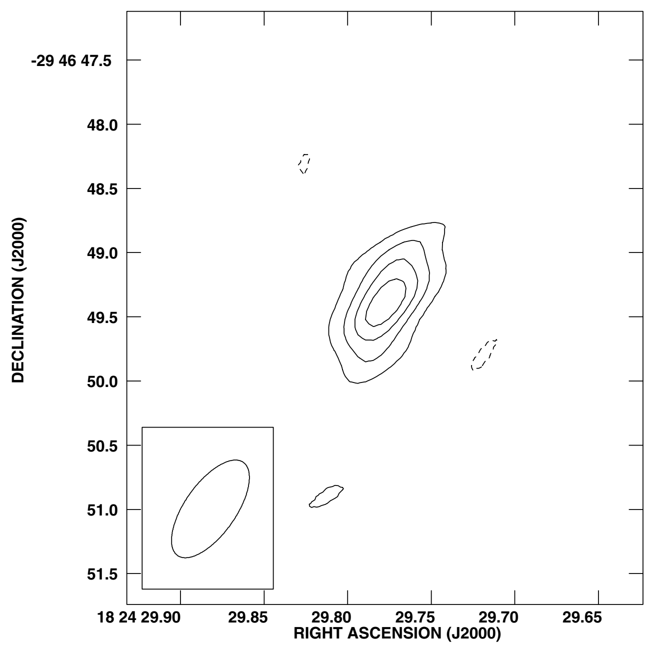

Figure 1. Contour map of the $\lambda = 7$ mm continuum emission of HD169142 observed with the VLA. Contour levels are −3, 3, 6, 9 and 12 × 0.3 mJy beam^{-1}, the rms of the map. The beam (size = 0.9 × 0.4 arcsec, PA = −35°) is shown in the lower left corner of the map. This bright (≃4.4 mJy beam^{-1}) unresolved (≲1 arcsec) 7 mm continuum source is most likely originated from dust emission in a circumstellar disc around HD169142 (see Section 3).

[1] The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

2.2 Spectral energy distribution

In Table 2, we list the flux density values of HD169142 from near-ultraviolet to radio wavelengths used for modelling the SED (Section 3). The magnitudes *UBV* and *JHK* measured by Malfait et al. (1998) and Sylvester et al. (1996) have been dereddened using a value of the extinction to the star of $A_V \simeq 0.5$, which is obtained from the standard extinction law with $R_V \simeq 3.1$ and a spectral type A5. Magnitudes have been converted into flux densities using zero points from Johnson (1966) and Bessell & Brett (1988). We also use *Infrared Space Observatory* (*ISO*) Short-Wavelength Spectrometer (SWS) data obtained towards HD169142 (Meeus et al. 2001).

3 DISCUSSION AND CONCLUSIONS

HD169142 is considered a relatively evolved Herbig Ae/Be star with an A5Ve spectral type (Dunkin et al. 1997). Therefore, its circumstellar envelope is likely gone and only the disc is responsible for the dust emission at all wavelengths. At present, HD169142 is one of the few intermediate-mass stars where emission at wavelengths as long as 7 mm has been detected. Consequently, the good wavelength coverage of the SED of HD169142, with observational data ranging from near-ultraviolet to radio frequencies (Table 2 and Fig. 2), makes this object a good candidate to find a self-consistent irradiated accretion disc model, with parameters reasonably well constrained.

Table 2. Flux density values of HD169142.[a]

λ (μm)	F_ν[b] (Jy)	Reference
0.36 (U)	2.0	1
0.45 (B)	5.38	2
0.55 (V)	4.56	2
0.90 (I)	1.79	2
1.22 (J)	2.0	2
1.65 (H)	1.78	2
2.20 (K)	1.58	2
3.45 (L)	1.61	1
3.80 (L')	1.29	1
4.8 (M)	0.96	1
10.8 (N)	2.37±0.2	3
12	2.95±0.3	4
18.2 (IHW)	7.86±0.8	3
25	18.4±1.8	4
60	29.6±3.0	4
100	23.4±2.3	4
450	3.34±0.115	5
800	0.554±0.034	2
850	0.565±0.1	5
1100	0.287±0.013	2
1300	0.197±0.015	2
2000	0.070±0.019	2
7000	0.0044±0.0009	6
35 000	⩽0.00008	6

References: (1) Malfait et al. (1998); (2) Sylvester et al. (1996); (3) Jayawardhana et al. (2001); (4) *IRAS* PSC; (5) Sandell & Weintraub (in preparation) and (6) this work.
[a]In addition to the values listed in this table, we also use *ISO* short-wavelength spectrometer data obtained towards HD169142 by Meeus et al. (2001).
[b]Uncertainties in the near-ultraviolet through near-IR flux densities are less than 10 per cent.

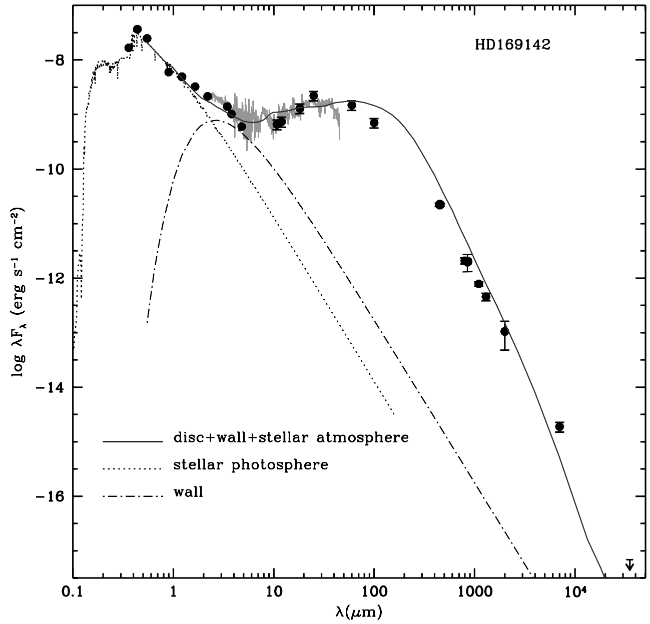

Figure 2. Observed and model SEDs for the source HD169142. The dotted line corresponds to the emission from the stellar photosphere of an A2 star with an age of 10 Myr. The dot–dashed line is the emission arising from the inner cylindrical surface where the disc is truncated by dust sublimation (the 'wall' with a height of 0.018 au). The solid line represents the total emission that includes the disc (whose physical parameters are $i = 30°$, $\dot{M}_{acc} = 10^{-8}$ M$_\odot$ yr^{-1}, $R_{disc} \simeq 300$ au and $a_{max} = 1$ mm), the stellar photosphere and the 'wall' contributions (see Section 3 and Table 3). Thin grey lines indicate *ISO* short-wavelength spectrometer values obtained by Meeus et al. (2001).

The observed SED (Fig. 2) exhibits three remarkable characteristics: strong millimetre emission, a shallow dependence of the long wavelength dust opacity on wavelength ($\kappa \propto \lambda^{-0.5}$, as indicated by the spectral index in the submillimetre and millimetre ranges, assuming the total flux density is dominated by optically thin emission) and the absence of a detectable silicate feature at 10 μm (Meeus et al. 2001). To account for the observed strong millimetre emission, either a massive disc or a dust mixture with large grains is required. If the disc is assumed to have interstellar-like grains, characterized by a small emissivity at millimetre wavelengths, then it is required to have a disc more massive than if the grains have a maximum size of around 1 mm (D'Alessio, Calvet & Hartmann 2001); in this last case, the grains have the largest possible emissivity at millimetre wavelengths and then the required mass of the disc is the minimum possible. In an accretion α-disc irradiated by the central star, the surface density Σ scales as $\dot{M}_{acc}/\alpha$ (D'Alessio et al. 1999), where $\dot{M}_{acc}$ is the disc mass accretion rate and α is the viscosity parameter (Shakura & Sunyaev 1973). Therefore, for a given disc radius, the increase in the disc mass resulting from increasing $\dot{M}_{acc}$ is equivalent to that produced by decreasing α by the same amount. If the value of the disc radius is constrained from observations, a massive disc can be obtained either with high values of $\dot{M}_{acc}$(>10^{-6} M$_\odot$ yr^{-1}) or by assuming small values of α. However a massive disc would probably imply a mid-IR emission higher than observed. A mixture including large grains is also favoured instead of a massive disc, because of the shallow dependence of the dust opacity with wavelength in the submillimetre and millimetre ranges (implying $\beta = 0.5$, where $\kappa \propto \lambda^{-\beta}$, while smaller grains have typically $\beta = 1.5$–2; see for example the dependence of the millimetre flux densities and slope on the grain size in fig. 8 of Osorio et al. 2003), the lack of silicate emission (see fig. 1 in D'Alessio et al. 2001) and the fact that massive discs may become gravitationally unstable (see below).

In order to derive the physical parameters of HD169142, we compare the observed SED with the data base of structural parameters and synthetic SEDs of irradiated disc models published by D'Alessio et al. (2005).[2] The SEDs in this catalogue include the contribution of an irradiated accretion disc, the contribution of the stellar photosphere (relevant in the optical regime) calculated using Kurucz (1993) models and the contribution of the inner cylindrical surface that faces the star, where the dust disc is truncated by dust sublimation at $T \simeq 1400$ K (i.e. the 'wall' at the dust destruction radius, $R_{\rm wall}$, whose emission is important in the near-IR range; Natta et al. 2001).

The main characteristics of these disc models are described in D'Alessio et al. (1998, 1999, 2001). In summary, these discs are assumed to be in steady state (with a constant $\dot{M}_{\rm acc}$) and geometrically thin (i.e. the gas scale height along the disc is smaller than the radial distance). They are heated by stellar radiation, viscous dissipation and ionization by energetic particles. The viscosity parameter α is calculated following the prescription from Shakura & Sunyaev (1973), where the usual value $\alpha = 0.01$ is adopted for all the models in the data base, except for the models with 4000 K and 1 Myr where values $\alpha = 0.1$, 0.01 and 0.001 were used. The opacity is mainly due to dust, whose grains are assumed to have a size distribution $n(a) \propto a^{-3.5}$ between a minimum size $a_{\rm min}$ (fixed at 0.005 μm) and a maximum size $a_{\rm max}$ (taken as a free parameter). In the models of D'Alessio and collaborators, the vertical structure and emission properties of the disc are calculated self-consistently with the stellar parameters, instead of using simple power-law descriptions for the dust temperature and the surface density.

In the case of HD169142, we have a priori constraints for some of the parameters. For instance, the spectral type of the star is A5Ve (Dunkin et al. 1997), the disc radius should be of the order of 100 au (a value suggested by the mid- and near-IR wavelength observations, see Section 1, as well as the 7 mm continuum observations presented in this paper), and the inclination angle of the disc with respect to the line-of-sight is $\simeq 10°$ [constrained by CO observations carried out by Dent et al. (2005)]. Thus, we have searched among the models of the D'Alessio et al. (2005) data base having these parameters close to the actual values of HD169142. In this way, we have selected an A2 star [whose mass $M_* = 2\,{\rm M}_\odot$ corresponds to a stellar luminosity $L_* = 17\,{\rm L}_\odot$ and radius $R_* = 1.7\,{\rm R}_\odot$, according to pre-main sequence tracks from Siess, Dufour & Forestini (2000)], a disc radius $R_{\rm disc} \simeq 300$ au and an inclination angle $i \simeq 30°$. We have estimated the values of the remaining parameters by fitting the observed SED. We obtain a reasonable fit by assuming a central star with an age of 10 Myr, surrounded by a disc with a mass accretion rate $\dot{M}_{\rm acc} \simeq 10^{-8}\,{\rm M}_\odot\,{\rm yr}^{-1}$, a mass $M_{\rm disc} \simeq 0.04\,{\rm M}_\odot$ (calculated by integrating the surface density in the disc, Σ, from the dust destruction radius, $R_{\rm wall} = 0.35$ au, to the outer radius, $R_{\rm disc} = 300$ au), and where dust grains have grown up to millimetre sizes ($a_{\rm max} = 1$ mm). We have modified the nominal value of the height of the 'wall' at the dust destruction radius used in the data base, in order to obtain a better fit to the observed near-IR emission. We obtained the best fit for a height of the dust wall $z_{\rm wall} = 0.018$ au. The gas scale height at $R_{\rm wall}$ can be calculated assuming that the dust there is vertically isothermal with a temperature of 1400 K. Using equation (13) of Dullemond et al. (2001), we obtain a value of ∼0.01 au for the gas scale height, implying a ratio of ∼2 between the height of the dust wall and the gas scale height. This low value of the ratio between the height of the dust wall and the gas scale height [as compared with the value of ∼4 usually found in HAeBe stars; Dullemond et al. (2001)] may imply that the dust in the inner disc has grown and is settling towards the equatorial disc plane, consistent with the large grains required to explain the 7 mm continuum emission. Fig. 2 shows the total emission of this model (solid line) which includes the disc contribution, the stellar photospheric contribution (dotted line) and the 'wall' emission (dot–dashed line).

[2] http://www.astrosmo.unam.mx/∼dalessio/

Table 3. Adopted parameters of the circumstellar disc around HD169142.[a]

Age (Myr)	$\dot{M}_{\rm acc}$ (${\rm M}_\odot\,{\rm yr}^{-1}$)	$L_{\rm acc}$ (${\rm L}_\odot$)	$R_{\rm wall}$ (au)	$R_{\rm disc}$ (au)	$M_{\rm disc}$ (${\rm M}_\odot$)	i (deg)	$a_{\rm max}$ (mm)	$z_{\rm wall}$ (au)
10	10^{-8}	0.37	0.35	300	0.04	30	1	0.018

[a]Obtained by modelling the observed SED (see Section 3).

We estimate the accretion luminosity as $L_{\rm acc} \simeq GM_*\dot{M}/R_* = 0.37\,{\rm L}_\odot$, which is considerably lower than the derived stellar luminosity ($L_* = 17\,{\rm L}_\odot$); irradiation is therefore the main heating agent of the disc upper layers. We note that some regions of the disc could be unstable to axisymmetric gravitational perturbations if the Toomre Q-parameter [$Q = (c_{\rm s}/\pi\Sigma)\,(M_*/GR^3)^{0.5}$, where $c_{\rm s}$ is the sound speed] is less than unity (Toomre 1964). Since the most unstable regions are expected to occur at large radii, we evaluated the Toomre Q-parameter at the disc radius ($R_{\rm disc} = 300$ au, where the surface density is 0.6 g cm^{-2} and the mid-plane temperature is 20 K, implying $c_{\rm s} = 0.3$ km s^{-1}) and we obtained a value of $Q \simeq 13$, implying that the disc is gravitationally stable. A disc ∼10 times more massive will be ∼10 times denser, and would start to become gravitationally unstable. A summary of the main parameters of the circumstellar disc around HD169142 is given in Table 3.

The SED of HD169142 has been modelled by Dominik et al. (2003) using a passive disc and dust grains with size $\simeq$0.1 μm. To fit the SED, Dominik et al. used a power-law radial distribution of surface density, with a very steep dependence, R^{-2}; in contrast, in the model outlined above the surface density is calculated self-consistently assuming an α-disc model and goes to an R^{-1} dependence at large radii (D'Alessio et al. 1999). In addition, Dominik et al. had to adopt a λ^{-1} dependence for the opacity in the millimetre range, which in our case arises naturally from the grain size distribution. Moreover, their predicted SED had significant silicate emission, while the large value of the grain maximum size of our adopted dust mixture consistently predicts no emission in this feature. In fact, the large grain sizes, the lack of silicate emission and the low height of the wall at the dust destruction radius all seem to suggest a large degree of grain coagulation and settling has occurred in the inner disc of HD169142. This is generally consistent with the predictions from models of the distribution of solids in proto-planetary discs (Weidenschilling 1997; Dullemond & Dominik 2004, 2005). Grains are shown to grow and settle very rapidly, possibly leaving a disc atmosphere dominated by smaller dust. The small grains can be replenished through mutual collisions. However, in the case of HD169142, the absence of a silicate feature suggests that few grains smaller than ∼3 μm exist in the disc atmosphere. The maintenance of relatively large grains in the atmosphere would require an efficient stirring mechanism; alternatively the dust could be depleted in silicate for some reason. Why the mm-sized grains have not settled further in such an old disc is unclear. However, the results of Dullemond & Dominik (2004) suggest that it is possible for a thin disc of relatively large grains to reach a semi-equilibrium state, given a suitably efficient stirring mechanism.

Finally, it is important to mention that the current model for HD169142 may not be unique, and that a model with a lower accretion rate ($\dot{M}_{\rm acc} \simeq 10^{-9}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$) and a smaller value of the viscosity parameter ($\alpha \simeq 0.001$) might be also feasible. In this sense, we also note that the slope of the model SED in the far-IR to submillimetre range is somewhat steeper than observed, suggesting that the power-law index of the dust grain size distribution is shallower than the value of -3.5 adopted here. Nevertheless, as pointed out by D'Alessio et al. (2005), to find a unique model, additional observational constraints such as spatial distribution profiles at various wavelengths are needed. In fact, the strong 7 mm dust continuum emission reported in this paper makes this source an excellent candidate to resolve its dust disc contents both at that particular wavelength with the VLA in its A configuration (angular resolution $\simeq$0.1 arcsec), and with the Expanded Submillimetre Array (eSMA = JCMT+SMA) at submillimetre wavelengths.

ACKNOWLEDGMENTS

We deeply thank the referee for her/his very stimulating comments and suggestions, which have been most useful in improving the scientific content of this paper. GA, MO and JMT are supported in part by Spanish AYA2002-00376 and AYA2005-08523 grants. GA and MO acknowledge partial support from Junta de Andalucía, Spain. MO acknowledges support from IAU Peter Gruber Foundation and MAE-AECI. We thank Gwendolyn Meeus for providing us the original *ISO* data.

REFERENCES

Acke B., van den Ancker M. E., Dullemond C. P., van Boekel R., Waters L. B. F. M., 2004, A&A, 422, 621
Acke B., van den Ancker M. E., Dullemond C. P., 2005, A&A, 436, 209
Bessell M. S., Brett J. M., 1988, PASP, 100, 1134
D'Alessio P., Cantó J., Calvet N., Lizano S., 1998, ApJ, 500, 411
D'Alessio P., Calvet N., Hartmann L., Lizano S., Cantó J., 1999, ApJ, 527, 893
D'Alessio P., Calvet N., Hartmann L., 2001, ApJ, 553, 321
D'Alessio P., Merín B., Calvet N., Hartmann L., Montesinos B., 2005, Rev. Mex. Astron. Astroffs., 41, 61
Dent W. R. F., Greaves J. S., Coulson I. M., 2005, MNRAS, 359, 663
Dominik C., Dullemond C. P., Waters L. B. F. M., Walch S., 2003, A&A, 398, 607
Dullemond C. P., Dominik C., 2004, A&A, 421, 1075
Dullemond C. P., Dominik C., 2005, A&A, 434, 971
Dullemond C. P., Dominik C., Natta A., 2001, ApJ, 560, 957
Dunkin S. K., Barlow M. J., Ryan S. G., 1997, MNRAS, 286, 604
Greaves J. S., Mannings V., Holland W. S., 2000, Icarus, 143, 155
Habart E., Natta A., Krugel E., 2004, A&A, 427, 179
Herbig G., 1960, ApJS, 4, 337
Hernández J., Calvet N., Hartmann L., Briceño C., Sicilia-Aguilar A., Berlind P., 2005, AJ, 129, 856
Hog E., Kuzmin A., Bastian, U., Fabricius C., Kuimov K., Lindegren L., Makarov V. V., Roeser S., 1998, A&A, 335, L65
Jayawardhana R., Fisher R. S., Telesco C. M., Piña R. K., Barrado y Navascués D., Hartmann L. W., Fazio G. G., 2001, AJ, 122, 2047
Johnson H. L., 1966, ARA&A, 4, 193
Kuhn J. R., Potter D., Parise B., 2001, ApJ, 553, L189
Kurucz R. L., 1993, ATLAS9 Stellar Atmosphere Programs and 2 km s^{-1} grid. CD-ROM No. 13. Smithsonian Astrophysical Observatory, Cambridge, MA
Malfait K., Bogaert E., Waelkens C., 1998, A&A, 331, 211
Mannings V., Sargent A., 1997, ApJ, 490, 792
Meeus G., Waters L. B. F. M., Bouwman J., van den Ancker M. E., Waelkens C., Malfait K., 2001, A&A, 365, 476
Natta A., Prusti T., Neri R., Wooden D., Grinin V. P., Mannings V., 2001, A&A, 371, 186
Natta A., Testi L., Neri R., Shepherd D. S., Wilner D. J., 2004, A&A, 416, 179
Osorio M., D'Alessio P., Muzerolle J., Calvet N., Hartmann L., 2003, ApJ, 586, 1148
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Siess L., Dufour E., Forestini M., 2000, A&A, 358, 593
Strom K. M., Strom S. E., Breger M., Brooke A. L., Yost J., Grasdalen G., Carrasco L., 1972, ApJ, 173, L65
Sylvester R. J., Skinner C. J., Barlow M. J., Mannings V., 1996, MNRAS, 279, 915
Toomre A., 1964, ApJ, 139, 1217
van den Ancker M. E., 1999, PhD thesis, University of Amsterdam
Weidenschilling S. J., 1997, Icarus, 127, 290

This paper has been typeset from a TEX/LATEX file prepared by the author.