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Evolution from protoplanetary to debris discs: the transition disc around HD 166191

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ABSTRACT

HD 166191 has been identified by several studies as hosting a rare and extremely bright warm debris disc with an additional outer cool disc component. However, an alternative interpretation is that the star hosts a disc that is currently in transition between a full gas disc and a largely gas-free debris disc. With the help of new optical to mid-infrared (IR) spectra and *Herschel* imaging, we argue that the latter interpretation is supported in several ways: (i) we show that HD 166191 is comoving with the ∼4-Myr-old Herbig Ae star HD 163296, suggesting that the two have the same age; (ii) the disc spectrum of HD 166191 is well matched by a standard radiative transfer model of a gaseous protoplanetary disc with an inner hole and (iii) the HD 166191 mid-IR silicate feature is more consistent with similarly primordial objects. We note some potential issues with the debris disc interpretation that should be considered for such extreme objects, whose lifetime at the current brightness is much shorter than the stellar age, or in the case of the outer component requires a mass comparable to the solid component of the solar nebula. These aspects individually and collectively argue that HD 166191 is a 4–5 Myr old star that hosts a gaseous transition disc. Though it does not argue in favour of either scenario, we find strong evidence for 3–5 μm disc variability. We place HD 166191 in context with discs at different evolutionary stages, showing that it is a potentially important object for understanding the protoplanetary to debris disc transition.

Key words: planets and satellites: formation – protoplanetary discs – circumstellar matter – stars: individual: HD 163296 – stars: individual: HD 166191.

1 INTRODUCTION

As nurseries in which planets form, protoplanetary discs are all-important in setting the boundary conditions for planet formation. One of their most important characteristics is the disc lifetime because once the gaseous component has dispersed, giant planet formation is halted. Therefore, the lifetime of protoplanetary discs and how they disperse has been the focus of many studies (e.g. Zuckerman, Forveille & Kastner 1995; Clarke, Gendrin & Sotomayor 2001; Haisch, Lada & Lada 2001; Adams et al. 2004; Mamajek et al. 2004; Chen et al. 2012) and sets hard constraints for models of giant planet formation.

The nature of the transition from a gaseous protoplanetary disc to a relatively gas-free debris disc is poorly understood, particularly the impact on the formation and evolution of planets and planetesimals.

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Observations at a range of infrared (IR) wavelengths are therefore vital to build up possible evolutionary sequences. Near-/mid-IR observations probe dispersal and the creation of inner holes in gas-rich 'transition' discs (Skrutskie et al. 1990; Muzerolle et al. 2010; Espaillat et al. 2012), and are also sensitive to warm dust created during the later stages of terrestrial planet formation (e.g. Melis et al. 2010; Jackson & Wyatt 2012). Far-IR observations are most sensitive to changes in the outer regions of protoplanetary discs as dust grains settle and grow, and to the same ∼100 au scales at which debris discs are typically observed around main-sequence stars.

For some evolved objects it is not clear whether the stars are still dispersing their gas and are in the 'transition' phase, or if the disc is sufficiently gas-free that it can be considered a true debris disc. Perhaps the best example is the extremely bright disc around HD 98800B ($L_{\rm disc}/L_\star \approx 2$ per cent; Zuckerman & Becklin 1993), which has been treated as either by different authors and illustrates that classification is not straightforward (Furlan et al. 2007; Wyatt et al. 2007). The recent discovery of H_2 emission, a signature of gas accretion, seems to favour the transition disc interpretation (Yang et al. 2012). Of course, there will be a continuum of objects between relatively gas-rich and gas-free discs, and no disc could ever be considered truly devoid of gas, but in order to create a useful evolutionary sequence it is important to interpret individual objects carefully. Doing so will, for example, ensure that unlikely scenarios are not invoked where simpler ones will suffice, and that observational sequences of objects are as close to reality as possible.

Here, we study an object that we suggest lies at the late end of the transition to a gas-free debris disc. HD 166191 has been known to have an IR excess above the expected photospheric level since it was observed with *Infrared Astronomical Satellite* (*IRAS*) and *Mid-Course Space Experiment* (*MSX*; Oudmaijer et al. 1992; Clarke, Oudmaijer & Lumsden 2005). The possibility of confusion of the *IRAS* emission with another nearby source, which is visible to the south-west in higher resolution images, meant that the excess was only detected unambiguously from 8 to 20 µm. More recently, this system was suggested to have a mid-IR excess with both *Wide-field Infrared Survey Explorer* (*WISE*; Kennedy & Wyatt 2013) and *Akari* (Fujiwara et al. 2013), which was confirmed with high-resolution mid-IR imaging (Schneider et al. 2013). While these studies went in search of warm terrestrial-zone debris discs, only Schneider et al. (2013) used the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004; Werner et al. 2004) to show that the far-IR emission is probably associated with the star, and therefore that the disc emission is significant over a wide range of wavelengths.

We previously argued that this star hosts a gas-rich disc based on the breadth of the disc spectrum and its brightness relative to the star (Kennedy & Wyatt 2013), but the other studies (Fujiwara et al. 2013; Schneider et al. 2013) have interpreted it as hosting a debris disc with two components (i.e. analogous to the asteroid and Edgeworth–Kuiper belts seen in our Solar system). Here we use several lines of evidence to argue that HD 166191 does indeed host a gaseous protoplanetary disc. After discussing the observations in Section 2, we show in Section 3 that HD 166191 has a common space motion with the ∼4-Myr-old Herbig Ae star HD 163296 suggesting that HD 166191 has a similar age. In Section 4 we highlight some potential issues with the debris disc interpretation and show that the HD 166191 disc emission is well modelled by a relatively normal transition disc, as might be expected for such a young star. Finally, we compare the HD 166191 disc to others, taking a close look at the 10 µm silicate feature and the overall disc spectrum, and discuss the implications of our work in Section 5.

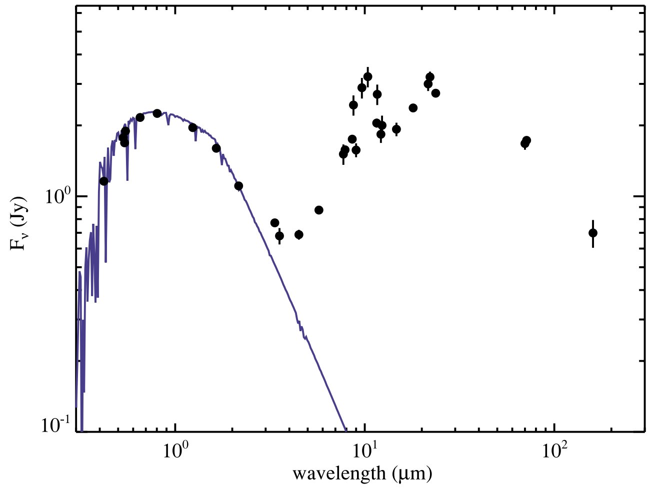

Figure 1. Photometry (dots) and the 6170 K PHOENIX AMES-Cond photosphere model (blue curve) for HD 166191.

2 OBSERVATIONS

HD 166191 is an 8.4th mag star that lies 119 pc from the Sun (van Leeuwen 2007) in the direction of the Galactic Centre. The Michigan spectral type is F4V, though using new data we suggest below that the star is actually closer to a late-F or early-G type, similar to the F8 spectral type found by Schneider et al. (2013). The star was detected by both *Hipparcos* and Two Micron All Sky Survey (2MASS), which we combine with *BVRI* photometry from Moffett & Barnes (1984) to fit a stellar photosphere model. We fitted PHOENIX AMES-Cond models (Brott & Hauschildt 2005) using least-squares minimization, finding an effective temperature of 6170 ± 50 K. A wealth of photometry exists for HD 166191, and is tabulated by Schneider et al. (2013) and shown in Fig. 1, including new *Herschel* observations described below. We do not use the *WISE* 4.6 µm (W2) measurement, as this is known to be overestimated for bright sources.[1]

2.1 New observations

To ensure that the far-IR excess was not confused in the MIPS 70 µm observations and to constrain the disc size we obtained 70 and 160 µm observations with Photodetector Array Camera and Spectrometer (PACS) instrument (Poglitsch et al. 2010) on the *Herschel Space Observatory* (Pilbratt et al. 2010) in 2013 March. In addition, we obtained ground-based optical, near- and mid-IR spectra with the goal of better characterizing the star and the near-/mid-IR excess.

2.1.1 SSO 2.3-m WiFeS

We observed HD 166191 with the Wide Field Spectrograph (WiFeS; Dopita et al. 2007) on the Australian National University (ANU) 2.3-m telescope at Siding Spring Observatory. Flux calibrations are performed according to Bessell (1999) using spectrophotometric standard stars from Hamuy et al. (1992) and Bessell (1999). A full description of the instrument configurations and data reduction procedure can be found in Penev et al. (2013). We use the $\lambda/\Delta\lambda = R = 3000$ blue arm spectrum to estimate the stellar

[1] http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec6_3c.html

effective temperature by comparison with model atmospheres. The method compares the spectrum with synthetic spectral models, with extra weight given to regions that are sensitive to surface gravity, and is described in detail by Bayliss et al. (2013). Assuming solar metallicity we obtain an effective temperature of 5965 ± 100 K, in reasonable agreement with the value derived from broad-band photometry above. The gravity is found to be $\log g = 3.4 \pm 0.25$, suggesting that HD 166191 has not yet reached the main sequence (see Section 3).

In the WiFeS $R = 7000$ red arm spectrum Li I absorption at 6708 Å (an indicator of youth in solar-type stars, see Section 3) is detected with an equivalent width of 150 ± 20 mÅ. From these observations we also obtained a radial velocity of -10.1 ± 1 km s^{-1}, in agreement with -8.1 ± 1.3 km s^{-1} reported by Schneider et al. (2013). Hydrogen α and β, and sodium doublet absorption are seen, so any gas accretion, which would result in emission (e.g. Muzerolle, Calvet & Hartmann 2001), is below a detectable level ($\lesssim 10^{-10}$–10^{-11} M$_\odot$ yr^{-1}; e.g. Muzerolle et al. 2003; Sicilia-Aguilar et al. 2006).

2.1.2 *IRTF/SpeX*

To further characterize the near-IR part of the excess, near-IR spectral measurements from 0.8 to 2.5 μm were obtained using the Spectropolarimeter for Planetary Exploration (SpeX) instrument on the 3-m NASA Infrared Telescope Facility (IRTF) located on Mauna Kea, Hawaii. It was operated in single prism mode ($R = 250$). Frames were taken so that the object was alternated between two different positions (usually noted as the 'A' and 'B' positions) on a 0.8 × 15 arcsec^2 slit aligned north–south. Two A0V stars were observed for telluric corrections, HD 168707 and HD 170364. Argon lamps were used for wavelength calibration. 24 images were taken with 1 s exposures and 10 co-adds and 16 images were taken with 0.5 s exposures and 10 co-adds. The airmass ranged from 1.41 to 1.47 during the observations.

The spectrum is shown in Fig. 2, along with a 6170 K model atmosphere (i.e. the same stellar model used in Fig. 1). At 2MASS K_s and beyond the possible onset of the IR excess is seen. An excess at these wavelengths is expected given that an excess is confidently detected beyond 3 μm.

By comparing the spectrum with the Rayner, Cushing & Vacca (2009) spectral atlas the spectral type appears to be late-F or early-G type. The Paschen δ, γ and β, and Brackett γ lines are clearly visible in the spectrum, and the atlas shows that these are present in F9V stars but less clear by G2V. Based on these lines and the effective temperatures derived above, we assign HD 166191 a G0V spectral type, with an uncertainty of one–two subtypes.

2.1.3 *AEOS/BASS*

Observations were obtained using the Aerospace Corporation's Broadband Array Spectrograph System (BASS; Hackwell et al. 1990) instrument on the 3.67-m Advanced Electro Optical System (AEOS) telescope on Haleakala, Hawaii. This instrument uses a cold beam splitter to separate the light into two separate wavelength regimes. The short-wavelength beam includes light from 2.9 to 6 μm, while the long-wavelength beam covers 6 to 13.5 μm. Each beam is dispersed on to a 58 element blocked impurity band linear array, thus allowing for simultaneous coverage of the spectrum from 2.9 to 13.5 μm. The spectral resolution is wavelength dependent, ranging from about $R = 30$ to 125 over each of the two wavelength

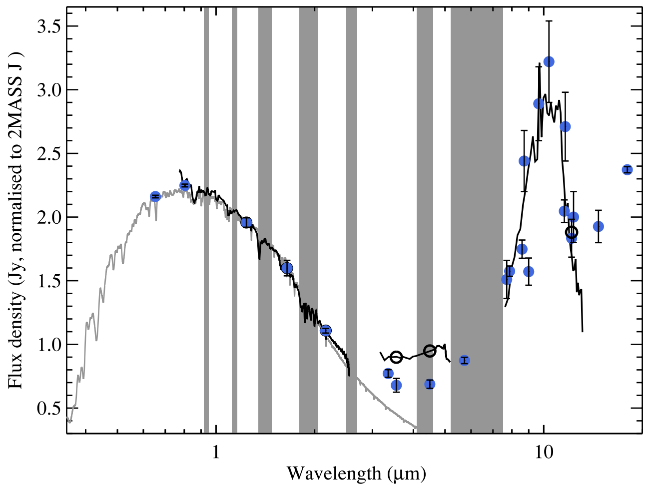

Figure 2. IRTF SpeX and BASS spectra, and a 6170 K model atmosphere convolved to approximately the same resolution. Filled blue dots show observed photometry and open circles show synthetic photometry of the spectra for comparison, where possible (*MSX* 12 μm, and IRAC 3.5 and 4.5 μm). The SPeX spectra is normalized to 2MASS *J*. Regions of large telluric absorption where the spectrum may be adversely effected are blocked out in grey. A small IR excess may be visible beyond about 2.1 μm in the SPeX spectrum, and clearly visible in the BASS spectrum. The difference between the IRAC 3.5 and 4.5 μm photometry and the equivalent spectrophotometry from BASS is significantly different, and indicate probable variability in the excess spectrum.

regions. The simultaneous coverage of the entire 3–13 μm region that BASS provides has played a critical role in the investigations of the clearing of the inner discs (Calvet et al. 2002; Bergin et al. 2004; Sitko et al. 2008).

The BASS data were calibrated using α Lyrae and β Peg and cleaned of residual telluric (CO_2 and H_2O) contamination, but that of O_3 at 9.7 μm was left in. The spectrum is shown in Fig. 2 and shows a clear silicate feature around 10 μm and is in good agreement with the T-ReCS photometry presented in Schneider et al. (2013). In addition, the absolute calibration of BASS spectra is known to be better than about 5 per cent (Russell et al. 2012), meaning that we can test for differences between the BASS spectrum and the older IRAC data (2006) at 3.5–4.5 μm (also shown in Fig. 2). The BASS/IRAC flux ratios in these bands are 1.32 and 1.38, with significances of 3.1σ and 4.5σ, indicative of significant variability in the excess spectrum. Schneider et al. (2013) note the possibility of variability based on the difference between IRAC and *WISE* photometry at 4.6 μm, but *WISE* is known to overestimate fluxes for bright sources in this band (see first footnote).

2.1.4 *Herschel*

Following identification of this object in Kennedy & Wyatt (2013), we obtained a Director's time observation of HD 166191 using the PACS instrument onboard *Herschel* (ObsIDs: 1342267772/3). We used a slightly non-standard miniscan map, designed to be wide enough to cover both HD 166191 and the nearby source that contaminates the *IRAS* photometry. The flux density of both objects was measured by fitting a model beam (an observation of γ Dra) at each location. We found fluxes of 1.7 ± 0.1 and 0.75 ± 0.1 Jy at 70 and 160 μm for HD 166191, consistent with the *Spitzer* photometry at 70 μm presented by Schneider et al. (2013). This observation further confirms that HD 166191 has a significant far-IR excess (see Fig. 1) and because the emission is point like (with beam size ∼5 arcsec) an approximate upper limit on the source diameter is ∼5 arcsec, or about 600 au.

2.2 Summary of observations

Based on previous data and the new observations described above we assign the star a spectral type of G0V. An IR excess is clearly visible beyond 3 µm, with a clear 10 µm silicate feature. A significant discrepancy between the IRAC and BASS observations at 3–5 µm suggests that the disc emission is variable, which is not unusual for transition discs (Bary, Leisenring & Skrutskie 2009; Muzerolle et al. 2009; Espaillat et al. 2011). The very large disc luminosity ($L_{\rm disc}/L_\star \approx 10$ per cent), the fact that the excess spectrum extends over a wide range of wavelengths (Fig. 1), and the probable variability suggests at first glance that the emission is probably from a young ($\lesssim$10 Myr old) star that hosts a gas-rich protoplanetary disc. However, it is also known that some debris disc brightnesses vary (e.g. Melis et al. 2012; Meng et al. 2012; Kennedy & Wyatt 2013), and an alternative interpretation could be that HD 166191 hosts an unusually bright debris disc with both warm and cool components (Fujiwara et al. 2013; Schneider et al. 2013), in essence an extreme analogue of the two-component debris disc around η Corvi (Wyatt et al. 2005; Smith, Wyatt & Haniff 2009). The most promising way to discern between these possibilities and to find a self-consistent explanation is to determine the age of HD 166191.

3 THE AGE OF HD 166191

There are several techniques available to infer the ages of young stars (e.g. Zuckerman & Song 2004; Soderblom 2010). In this section we attempt to refine the age of HD 166191 using the empirical methods of lithium depletion and X-ray activity, combined with kinematic considerations and (model-dependent) isochrone placement.

Because it is efficiently destroyed in stellar interiors, photospheric lithium abundance can serve as a mass-dependent clock over pre-main-sequence ages (Zuckerman & Song 2004; Murphy, Lawson & Bessell 2013). Our Li I λ6708 equivalent width, 150 ± 20 mÅ, agrees with the high-resolution value reported by Schneider et al. (2013), 120 ± 5 mÅ. At the spectral type of HD 166191 this value is consistent with an age less than the Pleiades ($\lesssim$100 Myr; Zuckerman & Song 2004). The poor age constraint of lithium depletion in solar-type stars is due to their radiative cores effectively separating the convective outer layers from the hotter interiors, preventing lithium depleted material from reaching the photosphere.

X-ray emission is another common diagnostic of stellar youth, a manifestation of the strong magnetic fields and fast rotation rates observed in young stars (e.g. Feigelson & Montmerle 1999). HD 166191 was not detected in the *ROSAT* All-Sky X-ray Survey (RASS). The RASS 0.1–2.4 eV limiting flux (2×10^{-13} erg cm^{-2} s^{-1}; Schmitt, Fleming & Giampapa 1995) at 119 pc implies an X-ray to bolometric luminosity ratio of $\log(L_{\rm X}/L_{\rm bol}) \lesssim -4.8$. Schneider et al. (2013) report a detection in the *XMM–Newton* Serendipitous Source Catalogue (Watson et al. 2009), which yields a 0.2–12 eV luminosity of 2.4×10^{29} erg s^{-1} and $\log(L_{\rm X}/L_{\rm bol}) \approx -4.9$. Ignoring the subtleties of comparing results from different X-ray observatories and energy bands, we compare these values to the results of Preibisch & Feigelson (2005), who examined the mass dependence of X-ray emission in young stars in Orion as a function of age. Their distributions show that while HD 166191 is one of the X-ray faintest 1–2 M$_\odot$ stars at 1–10 Myr ages, the X-ray luminosity also varies by about two orders of magnitude at a given age. Comparison with the X-ray luminosity distribution in Owen, Ercolano & Clarke (2011) leads to the same conclusion. Therefore, though it is indeed X-ray faint as noted by Schneider et al. (2013), we do not consider this faintness to provide a significantly stronger age constraint than the lithium absorption.

Kinematics are commonly used to assign young stars to moving groups or associations of known age. From *Hipparcos* astrometry (van Leeuwen 2007) and the 2.3-m/WiFeS radial velocity we calculate a heliocentric space motion for HD 166191 of $(U, V, W) = (-7.6 \pm 1.0, -22.4 \pm 3.0, -7.6 \pm 1.2)$ km s^{-1}. This agrees with the velocity presented by Schneider et al. (2013) from Tycho-2 proper motions. Fig. 3 shows the position and velocity of HD 166191 compared other nearby young stars. While the star's space motion is consistent with members of several young stellar associations, including the Scorpius–Centaurus (Sco–Cen) OB association, its relatively large distance (119^{+19}_{-14} pc) and low Galactic latitude yield a heliocentric position, $(X, Y, Z) = (+118 \pm 18, +15 \pm 2, -4 \pm 1)$ pc, distinct from other young groups in the solar neighbourhood.

Like Schneider et al. (2013), we searched for *Hipparcos* entries around HD 166191 with similar proper motions and parallaxes and found a match with the well-studied 'isolated' Herbig Ae star HD 163296 (119^{+12}_{-10} pc). Schneider et al. (2013) used the Extended Hipparcos Compilation (XHIP; Anderson & Francis 2012) radial velocity (-4.0 ± 3.3 km s^{-1}) for HD 163296 from Merrill (1930) via Gontcharov (2006). This is the mean velocity of a single line (Mg II λ4481) from seven Mt. Wilson plates ($\sigma_{\rm RV} = 9.4$ km s^{-1}). More recently, Buscombe & Kennedy (1965) and Alecian et al. (2013) reported larger velocities of −11 and -9 ± 6 km s^{-1}, respectively. Using the latter value and *Hipparcos* astrometry we calculate a space motion of $(U, V, W) = (-6.0 \pm 6.0, -22.3 \pm 2.1, -7.4 \pm 0.8)$ km s^{-1}, in excellent agreement with HD 166191.

A colour–magnitude diagram (CMD) of both stars is plotted in Fig. 4. If HD 166191 and HD 163296 are coeval then they should lie along the same theoretical isochrone in such a diagram. Compared to PARSEC (Bressan et al. 2012) and Siess et al. (2000) isochrones, HD 163296 has an age of 4–5 Myr, consistent with previous isochronal age estimates from a variety of model grids (Tetzlaff, Neuhäuser & Hohle 2011; Tilling et al. 2012; Alecian et al. 2013). HD 166191 falls slightly older, with an age of 5–10 Myr. This age agrees with the (conservative) 5^{+25}_{-3} Myr CMD age reported by Schneider et al. (2013) using the PARSEC models and 2MASS $K_{\rm s}$ magnitudes. We adopted the *J*-band photometry to minimize the effects of disc emission observed in both stars at wavelengths greater than 2 µm (see Section 2.1.2). The derived masses of HD 166191 are 1.7 and 1.6 M$_\odot$ from the PARSEC and Siess et al. (2000) isochrones, respectively. Neither star shows signs of unresolved binarity (Tilling et al. 2012; Schneider et al. 2013). Given their proximity (7.5 pc in space), identical distances, congruent space motions and very similar ages, it is likely HD 166191 and HD 163296 form a coeval, comoving pair of ∼4–5-Myr-old stars. HD 163296 was proposed as an outlying member of the 10–20-Myr-old Sco–Cen subgroup Upper Cen-Lup by Sitko et al. (2008). This membership is unlikely considering its young age and heliocentric position and velocity (Fig. 3). Instead, we speculate that HD 166191 and HD 163296 may represent the first members of a yet-to-be-discovered kinematic association or new Sco–Cen subgroup.

Having now established the likely youth of HD 166191 using a CMD and by association with HD 163296, it seems that a less extreme interpretation for the large IR excess may be that of a

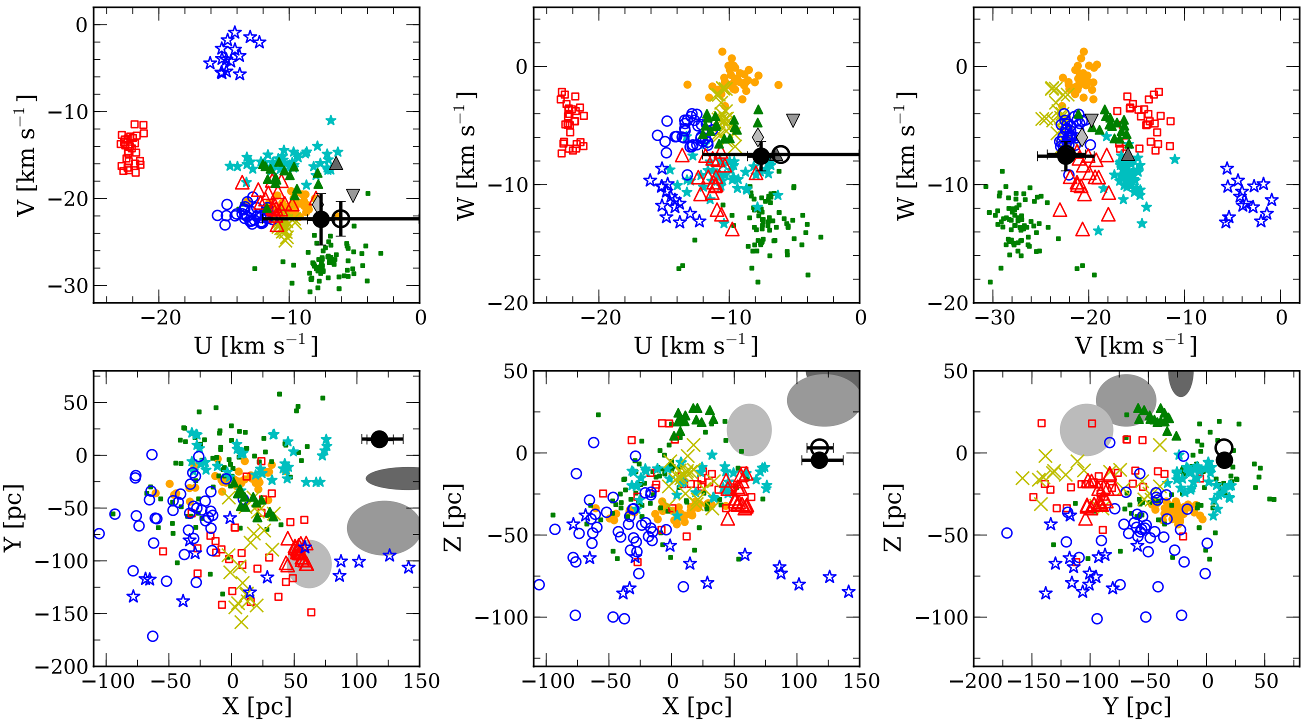

Figure 3. Heliocentric velocity (top) and position (bottom) of HD 166191 (black dot, with errors), compared to members of nearby associations and moving groups from Torres et al. (2008): Tuc-Hor (orange circles), AB Dor (green squares), Argus (red open squares), β Pic (cyan stars), Carina (yellow crosses), Columba (blue open circles), ϵ Cha (red triangles), Octans (blue open stars) and TW Hya (green filled triangles). Positions (shaded ellipses; Mamajek, Lawson & Feigelson 2000) and velocities (Chen et al. 2011) of the three Sco–Cen OB association subgroups are also plotted: Upper Sco (darkest, triangle), Upper Cen–Lup (inverted triangle) and Lower Cen–Cru (lightest, diamond). The large open circle shows the velocity and position of HD 163296.

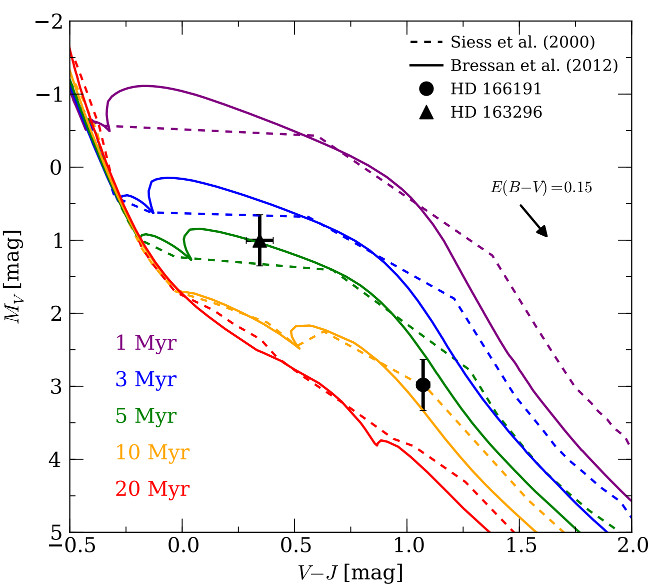

Figure 4. CMD of HD 166191 and HD 163296, with 3–20 Myr theoretical isochrones from Siess, Dufour & Forestini (2000) and Bressan et al. (2012) for comparison. For HD 163296, photometry and a (circumstellar) extinction of $E(B-V) = 0.15$ were adopted from Tilling et al. (2012). The Tycho-2 V-band magnitude for HD 166191 was transformed to the Johnson–Cousins system using the relations of Bessell (2000). No extinction was adopted for HD 166191.

gaseous transition disc, in contrast to the debris disc interpretation of Schneider et al. (2013).

4 DISC MODELLING

4.1 A two-belt debris disc?

The interpretation favoured by Schneider et al. (2013) is that HD 166191 hosts a warm terrestrial zone debris disc, the result of collisions between planetesimals or planets during the late stages of planet formation. However, the total fractional luminosity $f = L_{\rm disc}/L_\star$ of the excess spectrum is about 10 per cent, meaning that the dust in a putative debris disc must capture at least this much of the starlight. If the dust has a non-negligible albedo or is optically thick along the line of sight the fraction of starlight captured must be higher. As we show below, because such extreme IR excesses may require optically thick dust, significantly more than 10 per cent of the starlight may need to be captured. An additional complication in the case of HD 166191 is that Schneider et al. (2013) infer a cool outer component based on the breadth of the emission spectrum, with a fractional luminosity similar to the inner component. While such a two-belt structure is of course possible (e.g. the Solar system has two belts), the extreme brightness of the HD 166191 disc means that the inner belt must capture $\sim$6 per cent of the starlight, yet be sufficiently optically thin or misaligned that the outer belt is still able to capture $\sim$4 per cent. These constraints set lower limits on the vertical extent of the inner and outer belts, which can be compared with observations of edge-on belts around other stars.

To make a simple model of the above picture we assume that (i) the two belts are coplanar, (ii) have uniform density, (iii) the dust in the belts has negligible albedo, (iv) the belts are optically thin from the viewing direction and (v) re-emission from either belt does not heat the star or the other belt. We use parameters $f_{\rm i,\,o}$ and $\theta_{\rm i,\,o}$ for the fractional luminosity and opening angle of the inner (i) and outer (o) belts, respectively.

The radial optical depth of inner belt, $\tau_{\rm i}$, is related to the opening angle by

$$f_{\rm i} = \tau_{\rm i} \sin(\theta_{\rm i}/2). \quad (1)$$

That is, the fraction of starlight captured by the inner belt, and hence the fractional luminosity, is the radial optical depth multiplied by the fraction of the sky that it covers as seen by the star. When it is optically thick, increasing the radial optical depth does not increase the belt brightness (i.e. in equation 1, $\tau_{\rm i} \le 1$), so the opening angle of the inner belt must be at least 7°. The radial optical depth is correspondingly lower if the opening angle is larger, with a lower a limit of 0.06 if the belt is a spherical shell (i.e. $\theta_{\rm i} = 180°$).

The outer belt is always shadowed by the inner belt to some degree. If the opening angle of the outer belt is less than that of the inner belt, all light illuminating the outer belt must pass through the inner belt, with the light attenuated by a factor $1 - \tau_{\rm i}$ (with a minimum value of 0). If the inner belt is fatter than the outer belt, then only a fraction of the light heating the outer belt is intercepted by the inner belt, and the outer belt thickness is independent of the inner belt thickness (for fixed $f_{\rm i}$). In these two regimes, the radial optical depth of the outer belt, $\tau_{\rm o}$ (also $\le$1), is related to its opening angle and the inner belt properties by

$$f_{\rm o} = \begin{cases} \tau_{\rm o}(1 - \tau_{\rm i}) \sin(\theta_{\rm o}/2) & \theta_{\rm o} < \theta_{\rm i}, \\ \tau_{\rm o} (\sin(\theta_0/2) - f_{\rm i}) & \theta_{\rm o} > \theta_{\rm i}. \end{cases} \quad (2)$$

These relations are shown by the solid lines in Fig. 5, which uses the parameter space of $\theta_{\rm o}$ versus $\theta_{\rm i}$. Dashed lines show constant inner belt optical depth, where the minimum inner belt opening angle is set by $\tau_{\rm i} = 1$. The solid lines show equation (2) for three different inner belt optical depths. There are two different regimes for each line; if $\theta_{\rm o} < \theta_{\rm i}$ the outer belt is fully shadowed by the inner and there is a tradeoff between the opening angles of each, the thinner the inner belt, the more it shadows the outer belt due to increased optical depth, and the thicker the outer belt must be. This regime is shown by the curved part of the solid lines. If $\theta_{\rm o} > \theta_{\rm i}$ the outer belt is thicker than the inner and changes in the inner belt thickness do not change the outer belt brightness. That is, a thicker inner belt occults the outer belt more, but is less optically thick for the same fractional luminosity. The $\tau_{\rm o} = 1$ line tends towards, but never reaches $2\sin^{-1} f_{\rm o} \approx 5°$ for large $\theta_{\rm i}$, which would be the minimum opening angle in the absence of the inner belt.

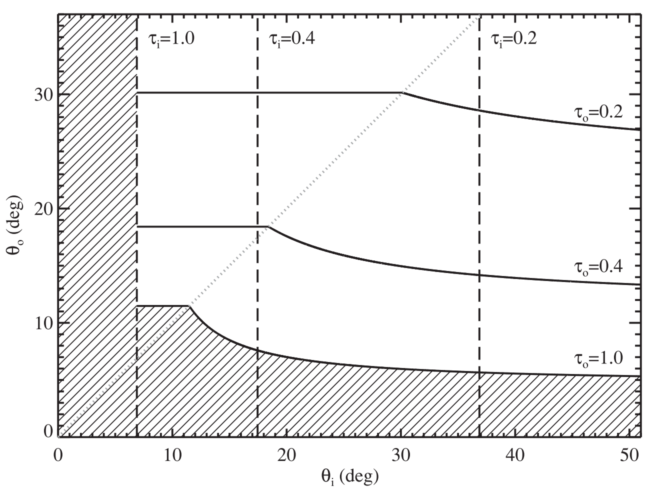

Figure 5. Simple model of allowed opening angles for a coplanar two-belt interpretation of HD 166191 with $f_{\rm i} = 0.06$ and $f_{\rm o} = 0.04$. The dashed lines show how the radial optical depth of the inner belt depends on the opening angle. The observed fractional luminosity cannot be produced for opening angles in the shaded regions (where $\tau_{\rm i,\,o} > 1$). The solid lines show constant radial optical depth for the outer belt (equation 2). The dotted line shows where the belts have equal opening angles.

Therefore, if both belts are to be relatively thin the minimum opening angles allowed by this simple analysis are about 7° for the inner component, and ~12° for the outer belt (i.e. the left end of the lowest solid line). This minimum assumes that both components are radially optically thick, and that no light is lost to scattering, the latter being a reasonable approximation given that typical albedoes for small bodies in the Solar system and in other debris discs are ~10 per cent (e.g. Kalas, Graham & Clampin 2005; Mueller et al. 2008; Fernández, Jewitt & Ziffer 2009; Krist et al. 2010). The other two solid lines show that even for larger opening angles the belts must have relatively large radial optical depths, purely due to the high fractional luminosity.

There are few debris discs where the opening angles can be measured, though a wealth of information is available for the Solar system. The inclinations of asteroid belt objects vary widely, with most objects below 10° (an opening angle of 20°), and similar values for Kuiper belt objects. Similarly, the full width at half-maximum brightness opening angle of the β Pictoris disc is ~10° at about 130 au (Golimowski et al. 2006), and the AU Microscopii disc is even thinner at ~5° (Krist et al. 2005). Therefore, the opening angles inferred for the inner and outer HD 166191 disc components are comparable with observed discs. However, this similarity requires that both components are radially optically thick *and* optically thin in the viewing direction, or the opening angles must be larger. For a typically inclined viewing geometry (~60°) such a configuration is unlikely, so unless the disc components are much more radially extended than they are vertically, and the system is viewed face-on, the opening angles are probably larger then our estimated minimum. The star is not seen to be reddened, and given the large optical depths seen in Fig. 5 the star is very probably seen directly and not obscured by the disc. In summary, this comparison is suggestive that the two-belt debris model requires relatively large optical depths for reasonable opening angles, but does not strongly argue against such an interpretation.

Now considering the plausibility of the debris disc interpretation in terms of a collisional model, the central issue is the lifetime of such extreme levels given the ~5 Myr age of HD 166191. As noted by Schneider et al. (2013), the dust lifetime due to collisions at about 1 au is only a few years so they must be replenished; a late-stage planetary embryo impact or ongoing collisions in a massive asteroid-belt analogue are the possible sources. While either the inner or outer disc component could be the result of a collision analogous to the Earth–Moon forming event, the extremely bright period that follows such a collision is probably short lived. The length of this period is uncertain due to the possibility of non-axisymmetry and an inability to remove dust at high optical depth, but given the rapid evolution shown in fig. 14 of Jackson & Wyatt (2012), less than 100–1000 yr seems a reasonable estimate. If the outer belt is several times more distant the emission will decay more slowly, by roughly a few orders of magnitude. Therefore, for a 5-Myr-old star it may be unlikely to observe short lived bright dust emission. However, this star was of course picked from a large sample of stars due to its extremely bright excess and several giant collisions are expected during terrestrial planet building (e.g. Chambers & Wetherill 1998; Raymond, Quinn & Lunine 2004; Kenyon & Bromley 2006).

The alternative scenario suggested by Schneider et al. (2013) is dust resulting from ongoing collisions in a massive asteroid belt. The issue here is the same as above; such extreme brightness requires a significant mass in large objects to generate a large surface area of dust, but this mass (and hence space density) also requires that the collisions between the large objects are very frequent. Indeed, Wyatt et al. (2007) showed using a simple collision model that the maximum fractional luminosity for young stars is ~0.1 per cent (see their fig. 3). Alternatively, using equation (21) of Wyatt et al. (2007), to maintain a fractional luminosity above 6 per cent, the maximum time the inner belt has been evolving for is of order 1000 yr, with a few orders of magnitude uncertainty (see also Heng & Tremaine 2010).

Another consideration for the massive asteroid-belt analogue scenario is the disc mass. Schneider et al. (2013) estimate the mass in dust present in the inner belt to be roughly 10^{20}–10^{23} g. However, because the debris disc interpretation explicitly implies that this mass is replenished by destruction of larger objects, the dust mass is a negligible fraction of the total mass for typical debris disc size distributions (e.g. Dohnanyi 1969; O'Brien & Greenberg 2003). Using equation (15) from Wyatt (2008) we can calculate the total mass present in a size distribution from 1 μm sized grains up to 100 km objects using a standard differential size distribution slope of −3.5. Converting the 760 and 175 K temperatures of the belts (Schneider et al. 2013) to radii of 0.3 and 6 au, and using the fractional luminosities of 0.06 and 0.04 yields total masses of 1.7 and 400 $M_\oplus$ for the inner and outer belts, respectively. For reference, the minimum mass contained in the solar nebula was a few hundred Earth masses (e.g. Weidenschilling 1977) so the inferred mass for the outer belt is very large, if relatively large planetesimals are assumed. For our assumed $\mathrm{d}n(a) \propto a^{-3.5}\mathrm{d}a$ particle size distribution, the total mass scales as the square root of the maximum size, so for much smaller 10-m planetesimals, the mass is also much smaller at 4 $M_\oplus$. However, the collisional lifetime calculated above is also a function of planetesimal size ($\propto\sqrt{D}$) and assumed $D = 2000$ km, so the outer belt lifetime for such small planetesimals would be of order 1000 yr. Therefore, there is a tradeoff between planetesimal size and disc lifetime, meaning that either the disc is relatively massive, or its lifetime at the current brightness is very short.

In summary, we cannot rule out the debris disc interpretation of Schneider et al. (2013). We have shown (i) that dust replenished by collisions either requires near optically thick belts or relatively large disc opening angles and (ii) that the outer belt is relatively massive if it is the result of ongoing collisions or has a very short lifetime. HD 166191 was selected as potentially interesting from a parent population of ≈24 000 *Hipparcos* stars (Kennedy & Wyatt 2013) and is therefore a rare object within this sample, meaning that arguments against the debris disc interpretation that rely on HD 166191 being observed at a special time may not be robust. As we have noted however, there is another possible interpretation; a protoplanetary disc made up of both gas and dust, as is seen around many stars that have similar ages to HD 166191.

4.2 A transition disc?

To test whether HD 166191 can be modelled as a protoplanetary disc we modelled the observed spectral energy distribution (SED) using the Monte Carlo radiative transfer code MCFOST (Pinte et al. 2006, 2009). Here, we used a parametric disc extending from an inner radius R_{in} to an outer radius R_{out}. With this approach, the model is of a dust disc that is implicitly well mixed with the gas that makes up most of the total mass in the disc. The dust density distribution has a Gaussian vertical profile, and the dust surface density profile and the scale height are defined as power-law distributions with $\rho(r, z) = \rho_0(r)\exp(-z^2/2h^2(r))$, $\Sigma(r) = \Sigma_0(r/r_0)^{-p}$ and $h(r) = h_0(r/r_0)^{\beta}$, respectively, where r is the radial coordinate in the equatorial plane and h_0 is the scale height at a fiducial radius $r_0 = 100$ au. The dust grains are assumed to be homogeneous and spherical amorphous silicates with a differential grain size distribution of the form $\mathrm{d}n(a) \propto a^{-3.5}\mathrm{d}a$, between a minimum grain size a_{min} and a maximum grain size a_{max}. The dust extinction and scattering opacities, scattering phase functions and Mueller matrices are calculated using Mie theory.

Table 1. Parameters of the best-fitting model.

Parameter	Explored range	Best value
	Stellar parameters	
T_{eff} (K)	Fixed	6000
R_{star} ($R_\odot$)	Fixed	2.13
A_V	Fixed	0.0
Distance (pc)	Fixed	119
	Disc parameters	
M_{dust} ($M_\odot$)	10^{-7}–10^{-4}	5×10^{-6}
R_{out} (au)	Fixed	25
R_{in} (au)	0.1–5.0	0.95
β	1.0–1.3	1.12
p	−2.0 to −0.1	−0.8
h_0 (au, $r = 100$ au)	1.0–15.0	3.8
inclin. (°)	0.0–90.0	<60
a_{min} (μm)	Fixed	0.03
$a_{\mathrm{max\text{-}amorph}}$ (μm)	0.5–1000.0	9.0
Amorph. to cryst. ratio	1.0–0.7	0.82

In order to fit the SED data, we first searched for a satisfactory solution by hand, which was used as the starting point for an automated best-fitting search with a genetic algorithm. In the absence of strong constraints from direct imaging (the *Herschel* observations require $R_{\mathrm{out}} \lesssim 300$ au), we have set the external radius $R_{\mathrm{out}} = 25$ au. This value is not well constrained by the SED modelling, in particular because of the lack of photometric data longer than 160 μm. The parameters of the best-fitting solution are presented in Table 1 and the resulting SED is presented in Fig. 6. The fit to the data is sufficiently good to show that the HD 166191 spectrum can be interpreted as a protoplanetary disc.

A prominent feature of the SED is the 10 μm silicate emission, though we did not thoroughly explore the mineralogical composition of the disc. However, to better match the general profile of the 10 μm feature we added a fraction of crystalline silicates (Li & Draine 2001) to the dust mixture. The crystalline silicates have a size distribution ranging from 0.03 to 5 μm. The amorphous silicates (of olivine stoichiometry; Dorschner et al. 1995) have a size distribution ranging from 0.03 to 9 μm. This value for the maximum size of the amorphous silicates is poorly constrained because of the lack of data longer than 160 μm. Both species are distributed similarly in the disc. The genetic algorithm found the best model for a composition made of 18 per cent of crystalline silicates, similar to the fraction of warm crystalline silicates found by Olofsson et al.

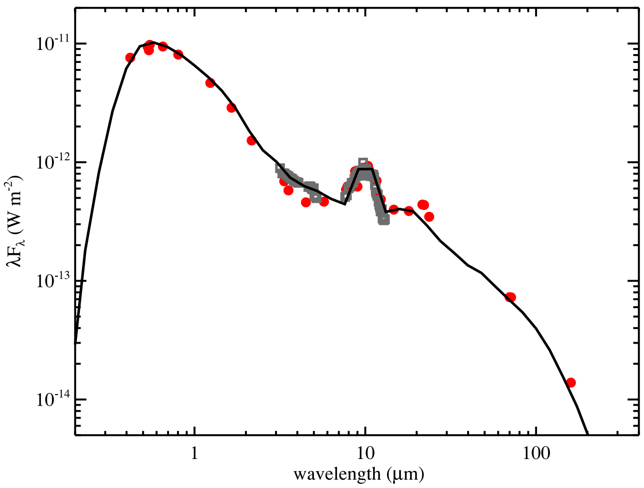

Figure 6. Protoplanetary transition disc model for HD 166191. Red dots show photometry and grey squares the BASS spectrum. The black solid line shows the best-fitting model as described in the text.

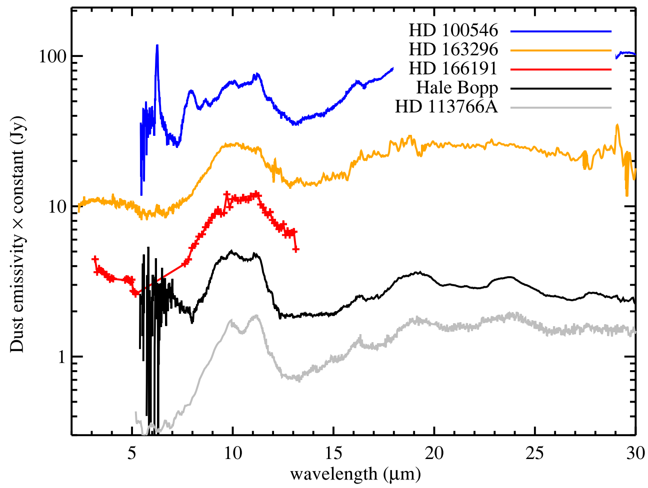

Figure 7. Comparison of the mid-IR emissivity of HD 166191 with other protoplanetary (HD 100546 and HD 163296) and debris (HD 113766A) discs, and comet Hale Bopp. The emissivity is calculated by dividing the spectrum by a blackbody at the approximate temperature of the continuum emission (e.g. Lisse et al. 2008).

(2010) in a study of 58 T Tauri stars with Infrared Spectrograph (IRS) spectra.

The resulting model requires the scale height to be about 4 au at $r = 100$ au (or $h/r = 0.04$). This is smaller than the 'standard' protoplanetary disc models that usually have $h/r \sim 0.1$, indicating that the dust has settled towards the midplane (e.g. Manoj et al. 2011; Sicilia-Aguilar et al. 2011). The derived inner radius of 0.95 au suggests that the disc has an inner hole, which along with the lack of detectable accretion (Section 2.1.1) is consistent with a several Myr-old object that has started the transition from a full protoplanetary disc to a debris disc. The inner hole size is smaller than most transition discs, but a wide range of sizes is seen (e.g. Andrews et al. 2011; Espaillat et al. 2012) so a ∼1 au hole is not particularly remarkable. The far-IR disc emission level is the main indicator of settling, which can be significantly brighter in other transition discs (see Fig. 8), suggesting that the progression towards the debris disc phase is more advanced for HD 166191 (e.g. Sicilia-Aguilar et al. 2011).

5 DISCUSSION

Perhaps the biggest clue to the status of HD 166191 is the common space motion with the well-known Herbig Ae star HD 163296. As outlined in Section 3, this association suggests that HD 166191 has a similar ∼4–5 Myr age to HD 163296, and these stars may represent the first few members of a yet-to-be discovered association or Sco–Cen subgroup that comprises many more lower mass stars.

The implication for HD 166191 itself is that the star probably hosts a protoplanetary disc rather than an exceptionally bright debris disc. The young age does not require that the disc is primordial, but places HD 166191 in the <10 Myr age range where Sun-like stars are seen to host such discs (e.g. Cieza et al. 2007; Carpenter et al. 2009; Williams & Cieza 2011). While we cannot rule out the extreme debris disc interpretation, we have noted potential issues (Section 4.1), and suggest that the disc is actually gas rich. Our protoplanetary disc interpretation is corroborated by the fact that the disc spectrum is consistent with a fairly standard model for a protoplanetary disc (see Section 4.2). The spectrum shows evidence for clearing in the innermost regions, as expected given typical evolutionary sequences, and grain settling in the outer regions, both signatures of discs whose evolution is well advanced beyond their initial state, as would be expected for a ∼5-Myr-old star.

Further clues to the nature of the disc lie in the BASS spectrum, which is compared to other discs and comet Hale Bopp's coma in Fig. 7. Here we have divided each spectrum by a blackbody at the appropriate temperature to produce 'emissivity' spectra, which far better show spectral features common to objects emitting at different temperatures.[2] Of particular note here is the similarity between the HD 166191 and HD 163296 peaks around 10 μm. Compared to HD 113766A, another candidate for ongoing terrestrial planet formation, the HD 166191 silicate peak is broader and is not double peaked.

Such differences in the shape of the silicate feature are diagnostic of the grain sizes and composition, which can subsequently be related to their evolutionary state. One approach is to derive compositions for objects of a range of age via modelling, and then comparing the results in terms of an evolutionary sequence. For example, Lisse et al. (2008) showed that their derived values for the olivine to pyroxene ratio change with age. Lisse et al. (2012) show the olivine to pyroxene ratio and total olivine fraction derived from modelling for 19 objects in their fig. 7. Older objects have greater olivine fractions, both in absolute terms and relative to pyroxene, with HD 163296 appearing as one of the least evolved objects and HD 113766A appearing as a moderately evolved object. Therefore, because the spectrum of HD 166191 appears very similar in shape to HD 163296, and different to HD 113766A, the evolutionary state of the HD 166191 dust appears more primordial. This conclusion would of course be strengthened by detailed modelling of a 5–35 μm spectrum, as was done for the other systems in Fig. 7, which allows for verification of the 8–13 μm silicate identifications using the secondary 16–33 μm silicate features. We thus look forward to obtaining a detailed spectrum of the HD 166191 system in the 13–30 μm range e.g. with *James Webb Space Telescope* (*JWST*).

[2] Using the temperatures of 250 and 135 K (HD 100546; Lisse et al. 2007), 300 K (HD 163296), 700 K (HD 166191), 200 K (Hale Bopp; Lisse et al. 2007) and 440 K (HD 113766A; Lisse et al. 2008).

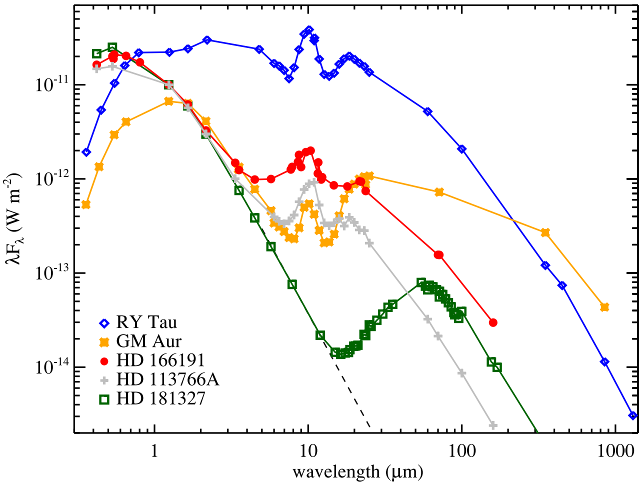

Figure 8. Comparison of HD 166191 with other protoplanetary (RY Tau, GM Aur) and debris (HD 113766A, HD 181327) discs. Data compiled from RY Tau, GM Aur (Robitaille et al. 2007), HD 113766A (Lisse et al. 2008; Olofsson et al. 2013) and HD 181327 (Lebreton et al. 2012), using *Spitzer* IRS (Houck et al. 2004) spectra from the CASSIS data base (Lebouteiller et al. 2011).

The overall disc spectrum should also be put in context with entire disc spectra at other stages to better picture HD 166191 as part of a possible evolutionary sequence. Fig. 8 compares the overall 0.5–160 μm HD 166191 SED with some examples of other protoplanetary and debris discs around (approximately) Sun-like stars, all scaled to a similar photospheric level at 2μm, with the exception of RY Tau for which the photosphere is not visible at this wavelength. We have not attempted to correct the shorter wavelength photometry for reddening as we are here concerned with the longer wavelengths. These represent something of an evolutionary sequence: (i) the youngest discs, represented here by RY Tau (Schegerer et al. 2008), have a relatively flat spectral slope across near-/mid-IR wavelengths, but at the onset of disc dispersal; (ii) an inner hole develops and the spectrum has a flux deficit in the mid-IR and little change in the far-IR and submillimetre flux (e.g. GM Aur; Calvet et al. 2005); (iii) the final debris disc phase begins when the gas disc is dispersed, and generally the disc has a spectrum that is typically very similar to a pure blackbody (e.g. HD 181327; Lebreton et al. 2012), but in some rare cases shows significant levels of warm emission, which is commonly interpreted as a sign of terrestrial planet formation (e.g. HD 113766A; Lisse et al. 2008; Olofsson et al. 2013). Both protoplanetary and debris discs show solid-state 10 μm silicate features, so their presence or otherwise does not indicate the evolutionary state in this broad comparison (though as discussed above their shape is important).

Within the context of this simple evolutionary sequence, HD 166191 shows characteristics that might individually be attributed to either a transitional or a debris disc. The disc shows evidence for an inner hole with little near-IR dust emission, though the hole is probably not as large or well cleared as for GM Aur given the larger mid-IR excess. In an inside-out evolution picture such as photoevaporation (e.g. Clarke et al. 2001), the HD 166191 disc might be considered less evolved than GM Aur in the inner regions. However, as we note below it may be that the inner emission is being enhanced by dust produced during terrestrial planet formation, which could happen before and/or after an inner hole develops. A significant difference with GM Aur is a lower level of far-IR and submillimetre excess, suggesting that the HD 166191 disc is significantly less flared as a result of a lower disc mass and/or dust grains settling to the disc midplane.

Indeed, comparison of the HD 166191 far-IR emission with HD 181327, a young (∼10 Myr) bright debris disc, shows that the two have similar levels of excess, and that both are lower than 'typical' protoplanetary discs such as RY Tau and GM Aur. This comparable level of far-IR flux suggests that in addition to being less flared, that the HD 166191 disc could be well advanced in the transition to a debris disc in the outer regions. Similarly evolved discs have been observed around lower mass stars (e.g. in Corona Australis; Sicilia-Aguilar et al. 2013), suggesting that such a spectrum is not particularly unusual. For example, in the F_{24}/F_{100} versus F_{24} diagram of Sicilia-Aguilar et al. (2013; their fig. 11), HD 166191 would lie among the 'depleted discs', indicating significant evolution and lower scale heights. How far advanced the transition to the debris disc phase is will require a gas detection or stringent limits.

Finally, comparing HD 166191 with HD 113766A, a bright warm debris disc, the 0.5–160 μm spectrum continua look very similar; HD 113766A plausibly looks like a somewhat more evolved and fainter version of HD 166191. Given that HD 166191 can be modelled as a transition disc, such a comparison suggests that the interpretation of HD 113766A, which has thus far been classed as a debris disc (e.g. Lisse et al. 2008; Smith, Wyatt & Haniff 2012; Olofsson et al. 2013), deserves further consideration. For example, it may be that the two-component structure inferred from the combination of mid-IR interferometry (Smith et al. 2012) and far-IR photometry (Olofsson et al. 2013) is indicative of an inner disc whose emission is brightest at two radial locations but is also significantly extended, as might be expected for a protoplanetary disc. However, Chen et al. (2006) set stringent limits on gas levels in the inner regions of the HD 113766A disc using the IRS spectrum, and the dust emission may therefore not be primordial without gas to protect it from radiation forces. In addition, we have already argued that HD 113766A appears more evolved based on the mid-IR silicate feature (Fig. 7). This possibility leads us to a third interpretation for the HD 166191 disc (that also applies to HD 113766A) that we have not yet considered; a combination of scenarios where the outer disc is still gaseous with significantly settled dust, while the inner regions are in the late stages of, or have already made, the transition to the debris phase. In this case the excess might be again thought of as comprising two components; an inner warm component due at least in part to ongoing terrestrial planet formation (but perhaps also the remnants of the protoplanetary disc), and a well settled outer component with residual gas. Remnant gas may help maintain dust levels produced by collisions, reducing the time-scale problems that arise in the debris disc scenario, where dust is removed easily by radiation forces.

Following such a phase, it may be that large cool discs such as HD 181327 emerge as the inner regions collide and decay, and are then observed around older stars as 'typical' (i.e. longer lived) debris discs at radii of tens to hundreds of au. There are several possible scenarios for this sequence however. For example, HD 166191 could already host a debris disc that lies inside the protoplanetary disc and is currently undetectable, but will emerge as the protoplanetary disc continues to disperse. Alternatively, it may be that the birth of a debris disc requires stirring of planetesimals to sufficient velocities through formation of large protoplanets, so the HD 166191 spectrum may in the future drop to much fainter levels, but then become brighter again once the debris phase begins (e.g. Kenyon & Bromley 2004; Currie et al. 2008).

The single most important difference between the scenarios we have discussed, and the fundamental difference between our transition disc interpretation and the debris disc interpretation of Schneider et al. (2013), is the presence or absence of gas. While the BASS spectrum is more similar to protoplanetary discs and argues that the silicate emission is relatively primordial, this signature comes from dust. A disc that is still in transition to the debris disc phase will have some remaining gas, while a true debris disc will have negligible gas. There is currently no evidence for gas in the HD 166191 disc, either from gas accretion on to the star nor directly from the disc (e.g. from near-IR CO emission in the SPeX spectrum). Indeed, one apparent reason Schneider et al. (2013) reject the ∼5 Myr age suggested by the CMD in favour of an older 10–100 Myr age is based on the lack of Hα emission. However, many young stars with protoplanetary discs are not seen to accrete gas, particularly transition discs (e.g. Sicilia-Aguilar, Henning & Hartmann 2010) and accretion is not necessarily expected during this phase either (e.g. Alexander, Clarke & Pringle 2006). Detection, or a strongly constraining non-detection, of gas around HD 166191 is therefore an obvious way in which the disc may be further characterized.

6 SUMMARY

HD 166191 has been known to host an infrared excess for several decades, but the origin of this excess was unclear. New surveys by the *Akari* and *WISE* telescopes have led to renewed interest, and suggestions that the excess is due to a rare bright debris disc (Fujiwara et al. 2013; Schneider et al. 2013) or an evolved protoplanetary disc (Kennedy & Wyatt 2013).

Though we cannot rule out the debris disc interpretation, we argue that the excess is most simply interpreted as a relatively normal protoplanetary transition disc. This conclusion is supported by our findings that (i) HD 166191 is very likely associated and coeval with the previously isolated ∼4-Myr-old Herbig Ae star HD 163296, (ii) the disc spectrum can be modelled by a protoplanetary transition disc and (iii) the mid-IR silicate feature is a good match to other young objects, such as HD 163296. This finding may represent the first hint of a new nearby young stellar association or subgroup of Sco–Cen.

By comparing HD 166191 with other known protoplanetary and debris discs, we argue that the HD 166191 disc is more evolved than most transition discs, and suggest some possible scenarios for the late stages of the protoplanetary to debris disc transition.

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REFERENCES

Adams F. C., Hollenbach D., Laughlin G., Gorti U., 2004, ApJ, 611, 360
Alecian E. et al., 2013, MNRAS, 429, 1001
Alexander R. D., Clarke C. J., Pringle J. E., 2006, MNRAS, 369, 229
Anderson E., Francis C., 2012, Astron. Lett., 38, 331
Andrews S. M., Wilner D. J., Espaillat C., Hughes A. M., Dullemond C. P., McClure M. K., Qi C., Brown J. M., 2011, ApJ, 732, 42
Bary J. S., Leisenring J. M., Skrutskie M. F., 2009, ApJ, 706, L168
Bayliss D. et al., 2013, AJ, 146, 113
Bergin E. et al., 2004, ApJ, 614, L133
Bessell M. S., 1999, PASP, 111, 1426
Bessell M. S., 2000, PASP, 112, 961
Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127
Brott I., Hauschildt P. H., 2005, in Turon C., O'Flaherty K. S., Perryman M. A. C., eds, The Three-Dimensional Universe with Gaia, ESA SP-576. ESA, Noordwijk, p. 565
Buscombe W., Kennedy P. M., 1965, MNRAS, 130, 281
Calvet N., D'Alessio P., Hartmann L., Wilner D., Walsh A., Sitko M., 2002, ApJ, 568, 1008
Calvet N. et al., 2005, ApJ, 630, L185
Carpenter J. M. et al., 2009, ApJS, 181, 197
Chambers J. E., Wetherill G. W., 1998, Icarus, 136, 304
Chen C. H. et al., 2006, ApJS, 166, 351
Chen C. H., Mamajek E. E., Bitner M. A., Pecaut M., Su K. Y. L., Weinberger A. J., 2011, ApJ, 738, 122
Chen C. H., Pecaut M., Mamajek E. E., Su K. Y. L., Bitner M., 2012, ApJ, 756, 133
Cieza L. et al., 2007, ApJ, 667, 308
Clarke C. J., Gendrin A., Sotomayor M., 2001, MNRAS, 328, 485
Clarke A. J., Oudmaijer R. D., Lumsden S. L., 2005, MNRAS, 363, 1111
Currie T., Kenyon S. J., Balog Z., Rieke G., Bragg A., Bromley B., 2008, ApJ, 672, 558
Dohnanyi J. S., 1969, J. Geophys. Res., 74, 2531
Dopita M., Hart J., McGregor P., Oates P., Bloxham G., Jones D., 2007, Ap&SS, 310, 255
Dorschner J., Begemann B., Henning T., Jaeger C., Mutschke H., 1995, A&A, 300, 503
Espaillat C., Furlan E., D'Alessio P., Sargent B., Nagel E., Calvet N., Watson D. M., Muzerolle J., 2011, ApJ, 728, 49
Espaillat C. et al., 2012, ApJ, 747, 103
Feigelson E. D., Montmerle T., 1999, ARA&A, 37, 363
Fernández Y. R., Jewitt D., Ziffer J. E., 2009, AJ, 138, 240
Fujiwara H. et al., 2013, A&A, 550, A45
Furlan E. et al., 2007, ApJ, 664, 1176
Golimowski D. A. et al., 2006, AJ, 131, 3109
Gontcharov G. A., 2006, Astron. Lett., 32, 759
Hackwell J. A., Warren D. W., Chatelain M. A., Dotan Y., Li P. H., 1990, Proc. SPIE, 1235, 171
Haisch K. E., Jr, Lada E. A., Lada C. J., 2001, ApJ, 553, L153
Hamuy M., Walker A. R., Suntzeff N. B., Gigoux P., Heathcote S. R., Phillips M. M., 1992, PASP, 104, 533
Heng K., Tremaine S., 2010, MNRAS, 401, 867
Houck J. R. et al., 2004, ApJS, 154, 18
Jackson A. P., Wyatt M. C., 2012, MNRAS, 425, 657
Kalas P., Graham J. R., Clampin M., 2005, Nature, 435, 1067
Kennedy G. M., Wyatt M. C., 2013, MNRAS, 433, 2334
Kenyon S. J., Bromley B. C., 2004, AJ, 127, 513
Kenyon S. J., Bromley B. C., 2006, AJ, 131, 1837
Krist J. E. et al., 2005, AJ, 129, 1008
Krist J. E. et al., 2010, AJ, 140, 1051
Lebouteiller V., Barry D. J., Spoon H. W. W., Bernard-Salas J., Sloan G. C., Houck J. R., Weedman D. W., 2011, ApJS, 196, 8
Lebreton J. et al., 2012, A&A, 539, A17
Li A., Draine B. T., 2001, ApJ, 550, L213
Lisse C. M., Kraemer K. E., Nuth J. A., Li A., Joswiak D., 2007, Icarus, 187, 69
Lisse C. M., Chen C. H., Wyatt M. C., Morlok A., 2008, ApJ, 673, 1106
Lisse C. M. et al., 2012, ApJ, 747, 93
Mamajek E. E., Lawson W. A., Feigelson E. D., 2000, ApJ, 544, 356
Mamajek E. E., Meyer M. R., Hinz P. M., Hoffmann W. F., Cohen M., Hora J. L., 2004, ApJ, 612, 496
Manoj P. et al., 2011, ApJS, 193, 11
Melis C., Zuckerman B., Rhee J. H., Song I., 2010, ApJ, 717, L57

Melis C., Zuckerman B., Rhee J. H., Song I., Murphy S. J., Bessell M. S., 2012, Nature, 487, 74
Meng H. Y. A., Rieke G. H., Su K. Y. L., Ivanov V. D., Vanzi L., Rujopakarn W., 2012, ApJ, 751, L17
Merrill P. W., 1930, ApJ, 72, 98
Moffett T. J., Barnes T. G., III, 1984, ApJS, 55, 389
Mueller M., Grav T., Trilling D., Stansberry J., Sykes M., 2008, BAAS, 40, 511
Murphy S. J., Lawson W. A., Bessell M. S., 2013, MNRAS, 435, 1325
Muzerolle J., Calvet N., Hartmann L., 2001, ApJ, 550, 944
Muzerolle J., Hillenbrand L., Calvet N., Briceño C., Hartmann L., 2003, ApJ, 592, 266
Muzerolle J. et al., 2009, ApJ, 704, L15
Muzerolle J., Allen L. E., Megeath S. T., Hernández J., Gutermuth R. A., 2010, ApJ, 708, 1107
O'Brien D. P., Greenberg R., 2003, Icarus, 164, 334
Olofsson J., Augereau J.-C., van Dishoeck E. F., Merín B., Grosso N., Ménard F., Blake G. A., Monin J.-L., 2010, A&A, 520, A39
Olofsson J., Henning T., Nielbock M., Augereau J.-C., Juhàsz A., Oliveira I., Absil O., Tamanai A., 2013, A&A, 551, A134
Oudmaijer R. D., van der Veen W. E. C. J., Waters L. B. F. M., Trams N. R., Waelkens C., Engelsman E., 1992, A&AS, 96, 625
Owen J. E., Ercolano B., Clarke C. J., 2011, MNRAS, 412, 13
Penev K. et al., 2013, AJ, 145, 5
Pilbratt G. L. et al., 2010, A&A, 518, L1
Pinte C., Ménard F., Duchêne G., Bastien P., 2006, A&A, 459, 797
Pinte C., Harries T. J., Min M., Watson A. M., Dullemond C. P., Woitke P., Ménard F., Durán-Rojas M. C., 2009, A&A, 498, 967
Poglitsch A. et al., 2010, A&A, 518, L2
Preibisch T., Feigelson E. D., 2005, ApJS, 160, 390
Raymond S. N., Quinn T., Lunine J. I., 2004, Icarus, 168, 1
Rayner J. T., Cushing M. C., Vacca W. D., 2009, ApJS, 185, 289
Rieke G. H. et al., 2004, ApJS, 154, 25
Robitaille T. P., Whitney B. A., Indebetouw R., Wood K., 2007, ApJS, 169, 328
Russell R. W. et al., 2012, in 21st CalCon. Space Dynamics Laboratory, Utah
Schegerer A. A., Wolf S., Ratzka T., Leinert C., 2008, A&A, 478, 779
Schmitt J. H. M. M., Fleming T. A., Giampapa M. S., 1995, ApJ, 450, 392
Schneider A., Song I., Melis C., Zuckerman B., Bessell M., Hufford T., Hinkley S., 2013, ApJ, 777, 78
Sicilia-Aguilar A., Hartmann L. W., Fürész G., Henning T., Dullemond C., Brandner W., 2006, AJ, 132, 2135
Sicilia-Aguilar A., Henning T., Hartmann L. W., 2010, ApJ, 710, 597
Sicilia-Aguilar A., Henning T., Dullemond C. P., Patel N., Juhász A., Bouwman J., Sturm B., 2011, ApJ, 742, 39
Sicilia-Aguilar A., Henning T., Linz H., André P., Stutz A., Eiroa C., White G. J., 2013, A&A, 551, A34
Siess L., Dufour E., Forestini M., 2000, A&A, 358, 593
Sitko M. L. et al., 2008, ApJ, 678, 1070
Skrutskie M. F., Dutkevitch D., Strom S. E., Edwards S., Strom K. M., Shure M. A., 1990, AJ, 99, 1187
Smith R., Wyatt M. C., Haniff C. A., 2009, A&A, 503, 265
Smith R., Wyatt M. C., Haniff C. A., 2012, MNRAS, 422, 2560
Soderblom D. R., 2010, ARA&A, 48, 581
Tetzlaff N., Neuhäuser R., Hohle M. M., 2011, MNRAS, 410, 190
Tilling I. et al., 2012, A&A, 538, A20
Torres C. A. O., Quast G. R., Melo C. H. F., Sterzik M. F., 2008, in Reipurth B., ed., Handbook of Star Forming Regions. Astron. Soc. Pac., San Francisco, Vol. II, p. 757
van Leeuwen F., 2007, A&A, 474, 653
Watson M. G. et al., 2009, A&A, 493, 339
Weidenschilling S. J., 1977, Ap&SS, 51, 153
Werner M. W. et al., 2004, ApJS, 154, 1
Williams J. P., Cieza L. A., 2011, ARA&A, 49, 67
Wyatt M. C., 2008, ARA&A, 46, 339
Wyatt M. C., Greaves J. S., Dent W. R. F., Coulson I. M., 2005, ApJ, 620, 492
Wyatt M. C., Smith R., Greaves J. S., Beichman C. A., Bryden G., Lisse C. M., 2007, ApJ, 658, 569
Yang H. et al., 2012, ApJ, 744, 121
Zuckerman B., Becklin E. E., 1993, ApJ, 406, L25
Zuckerman B., Song I., 2004, ARA&A, 42, 685
Zuckerman B., Forveille T., Kastner J. H., 1995, Nature, 373, 494

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