CO emission from discs around isolated HAeBe and Vega-excess stars

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ABSTRACT

We describe results from a survey for J=3-2 $^{12}$CO emission from visible stars classified as having an infrared excess. The line is clearly detected in 21 objects, and significant molecular gas ($\geq 10^{-3}$ Jupiter masses) is found to be common in targets with infrared excesses $\geq 0.01$ (\geq 56 per cent of objects), but rare for those with smaller excesses ($\sim$10 per cent of objects).

A simple geometrical argument based on the infrared excess implies that disc opening angles are typically $\geq 12^\circ$ for objects with detected CO; within this angle, the disc is optically thick to stellar radiation and shields the CO from photodissociation. Two or three CO discs have an unusually low infrared excess ($\leq 0.01$), implying the shielding disc is physically very thin ($\leq 1^\circ$).

Around 50 per cent of the detected line profiles are double-peaked, while many of the rest have significantly broadened lines, attributed to discs in Keplerian rotation. Simple model fits to the line profiles indicate outer radii in the range 30-300 au, larger than found through fitting continuum SEDs, but similar to the sizes of debris discs around main sequence stars. As many as 5 have outer radii smaller than the Solar System (50 au), with a further 4 showing evidence of gas in the disc at radii smaller than 20 au. The outer disc radius is independent of the stellar spectral type (from K through to B9), but there is evidence of a correlation between radius and total dust mass. Also the mean disc size appears to decrease with time: discs around stars of age 3-7 Myr have a mean radius $\sim210$ au, whereas discs of age 7-20 Myr are a factor of 3 smaller. This shows that a significant mass of gas (at least 2M$_\oplus$) exists beyond the region of planet formation for up to $\sim$7 Myr, and may remain for a further $\sim$10 Myr within this region.

The only bona fide debris disc with detected CO is HD9672; this shows a double-peaked CO profile and is the most compact gas disc observed, with a modelled outer radius of 17 au. In the case of HD141569, detailed modelling of the line profile indicates gas may lie in two rings, with radii of 90 and 250 au, similar to the dust structure seen in scattered light and the mid-infrared. In both AB Aur and HD163296 we also find the sizes of the molecular disc and dust scattering disc are similar; this suggests that the molecular gas and small dust grains are closely co-located.

Key words: stars: lines - spectra.

1 INTRODUCTION

Vega-excess stars were initially identified as being apparently normal main-sequence stars with an excess of emission above that of the photosphere at $\lambda \geq 12$ \micron (Aumann et al., 1984). Several lists of these objects have been compiled, such as that of Mannings & Barlow (1998), who cross-compared the IRAS Faint Source and the Michigan Spectral Catalogues. They found a total of $\sim$110 stars with detectable excesses, of which around 60 per cent are of spectral type B or A. Their Spectral Energy Distributions (SEDs) are very similar to many objects at the later stages of pre-main-sequence evolution, such as Herbig AeBe stars. HAeBe stars have spectral types later than B8 with clear optical emission lines and nearby nebulosity, both indicative of youth (Herbig, 1960). They are assumed to be the high-mass equiva-
lents of T Tauri stars. Thé et al. (1994) identified ~115 bona fide HAeBe candidates, and extended the spectral range to Fe stars. Many of the classical HAeBe stars are associated with nearby star formation, such as ambient molecular gas, optical nebulosity, outflows or infalling envelopes; typically this is found at radii of $\sim 10^3$ – $10^4$ au, and so can confuse studies of the stars themselves. However, Grinen et al. (1991), Meeus et al. (2001) and others identified a subclass of these stars which are relatively isolated, having no nearby cloud and a low line-of-sight extinction. The absence of nearby active star formation suggests that they are older than their classical brethren. Comparison with stellar evolutionary tracks give ages of a few Myr (e.g. van den Ancker et al., 1998), as compared with $10^4$ – $10^5$ yr for classical HAeBe stars (e.g. Fuente et al., 2002; Greaves et al., in prep.). Observations of these isolated stars are easier to interpret as their circumstellar disc emission is less confused by the ambient gas envelope (e.g. Dominik et al., 2003).

Because of the similarity of the SEDs, there is some confusion in the classification of Vega-excess and HAeBe stars. Dunkin et al. (1997) and Coulson et al. (1998) suggested some of the “dusty” Vega-excess objects are actually at an intermediate stage between HAeBe and main-sequence Vega-type stars. This class of isolated HAeBe star or dusty Vega-excess object may be therefore lie at an important evolutionary stage at the end of the pre-main-sequence phase, and are therefore sometimes known as “transition” objects (e.g. Malfait et al., 1998).

The material around HAeBe and Vega-excess stars is most commonly studied in dust continuum emission. However, molecular gas - traced by the low-J lines of CO - has also been detected in a small number of objects (e.g. Zuckerman et al., 1995; Coulson et al., 1998; Greaves et al., 2000; Thi et al., 2001). In many cases the signal:noise has been too low to obtain details of the line profiles, although some show a double-peaked line. In five of the brightest objects, the line emission has been resolved using mm-wave interferometry, revealing that the gas is located in a rotating disc (Manning & Sargent, 1997, 2000; Piétu et al., 2003). A disc would also explain the simultaneous high fractional excess emission, and low visual extinction (e.g. van den Ancker et al., 1998). Attempts to detect mm-wave CO emission from the archetypal Vega-excess stars such as Vega and $\beta$ Pictoris have proved unsuccessful, with measured CO/dust depletions of more than $10^3$ (Dent et al., 1995; Lisieux, 1999). This is likely to be caused by photodissociation from stellar UV; however if there remain some regions of the disc where the optical extinction to the star and interstellar radiation field is $\geq 3$ mag, significant CO could still be present (e.g. Greaves et al., 2000; Kamp et al., 2003).

The following observations comprise a more general survey of infrared excess stars for molecular gas, as traced by the J=3-2 transition of $^{12}$CO. Targets are identified as either Vega-excess or isolated HAeBe stars. We have then compared the line profiles with a simple disc model to determine some of the basic system parameters.

## 2 OBSERVATIONS

The data were taken using the facility heterodyne receiver RxB3 on the JCMT. Observations were made at the $^{12}$CO J=3-2 line rest frequency of 345.796 GHz, using the secondary chopper to obtain a sky reference 150 arcsec distant in azimuth. Spectra from both orthogonally-polarised mixers were averaged together. Total integration times were 30 or 60 minutes, although a few selected stars were targeted for longer integrations (up to 8 hours) to better delineate the line shapes. Most data were obtained as part of a poor-weather backup program carried out between 2000 September and 2001 January, and 2003 January to April. A few longer integration observations of selected targets were carried out in 2004 June. Additional data were also obtained from the JCMT archive, a subset of which has previously been published (Coulson et al., 1998; Greaves et al., 2000; Thi et al., 2001). In these cases, we have coadded the existing JCMT data with the new results in order to increase the effective integration time.

The target list was taken from the following surveys:

- The list of Vega-like systems with bright IRAS excesses from Sylvester et al. (1996) (17 out of their 24 stars).
- Young (1-10 Myr) stars with associated dust from Zuckerman et al. (1995) (13 out of 16 stars).
- Vega-excess stars with the largest far-infrared flux from Mannings & Barlow (1998).
- Isolated HAeBe stars from Malfait et al. (1998), van den Ancker et al. (1998) and Grady et al. (1996).

As mentioned above, in many cases the simple identification of a star as luminosity Class V with an IRAS excess means that the target list includes both isolated Herbig HAeBe or even T Tauri stars, as well as Vega-excess stars. We have avoided the classical embedded HAeBe stars. In addition, a small number of stars have subsequently been identified being luminosity Class III or IV, or have revised distance estimates; these have been identified in the analysis.

The basic target information and results are given in Table 1; distances in most cases are from the Hipparcos catalogue and when not available we have used literature values or those derived from the visual magnitude. Also listed are the fractional excess luminosities, $f$, i.e. the luminosity radiated from the system in excess of the photosphere, as a fraction of the total stellar photospheric emission. In most cases $f$ is obtained from the literature, or by fitting modified black-bodies to the available optical through to sub-mm fluxes. This fitting assumes in most cases a single temperature for the dust, with an opacity index, $\beta = 1.0$ (e.g. Dent et al., 2000). The typical uncertainty in the fractional excess is estimated to be a factor of two, mostly due to the incomplete wavelength coverage.

The CO integrated emission or 1-$\sigma$ upper limits are given in the Table. In the case of a line detection, the centroid CO velocity and the stellar velocity from the literature are also listed. In most cases these are in reasonable agreement, giving confidence that the observed gas is associated with the star and not with background Galactic emission. Despite the targeting of isolated objects, 3 or 4 objects showed bright, narrow positive or negative lines, indicating an extended ambient cloud either associated with the star or along the line of sight.
Table 1. Target stars and observational results.

| HD name | Other name | Sp. type(1) | d[(2)] (pc) | f[(3)] | CO intensity[(4)] (K km s\(^{-1}\)) | v\(_{CO}\) (km s\(^{-1}\)) | v\(_{s}\) (km s\(^{-1}\)) | Notes[(7)] & references |
|----------|------------|-------------|-------------|--------|---------------------------------|----------------|----------------|-------------------------|
| 627      | AB Aur     | A0V         | 144         | 0.48   | 7.4\(\pm\)0.17                | 15.1           | 8\(\pm\)5        | D. MS97,M01             |
| 6250     | MWC480     | A5V         | 131         | 0.2    | 2.74\(\pm\)0.06               | 14.5           | -              | D. MS97,S01             |
| 32509    | A2V        | 150         | 0.016       | 0.11   |                                 |                 |                |                         |
| 34282    | A0.5V      | 400         | 0.39        | 0.11   |                                 |                 |                |                         |
| 35833    | A9V        | 267         | 0.02        | 0.17   |                                 |                 |                |                         |
| 50138    | B8V(6)     | 289         | 0.6         | 0.074  |                                 |                 |                |                         |
| 53833    | A9V        | 267         | 0.02        | 0.25   |                                 |                 |                |                         |
| 56847    | B9IV       | 280         | 0.15        | 0.11   |                                 |                 |                |                         |
| 81515    | A5V        | 106         | 6.1\(\times\)10\(^{-3}\) | 0.09   |                                 |                 |                |                         |
| 98800    | K4V        | 46          | 0.084       | <0.09  |                                 |                 |                |                         |
| 102647   | A3V        | 11          | 1.9\(\times\)10\(^{-5}\) | 0.18   |                                 |                 |                | S96                    |
| 109085   | F2V        | 18          | 6.9\(\times\)10\(^{-5}\) | 0.08   |                                 |                 |                |                         |
| 121847   | 47 Hya     | B8V        | 104         | 2.4\(\times\)10\(^{-4}\) | <0.07  |                 |                |                         |
| 123247   | B9.5V      | 101         | 1.3\(\times\)10\(^{-4}\) | 0.3    |                                 |                 |                |                         |
| 123356   | G1V        | 41          | 6.1\(\times\)10\(^{-3}\) | 0.07   |                                 |                 |                |                         |
| 135344   | SAO206462  | F4V        | 84r         | 0.44   | 0.97\(\pm\)0.04               | 2.9            | -3\(\pm\)3       | D. S96,CWD98,T01,M01,D03 |
| 139365   | B2.5V      | 136         | 1.4\(\times\)10\(^{-5}\) | 0.063  |                                 |                 |                |                         |
| 139450   | G0/1V      | 73          | 2.4\(\times\)10\(^{-3}\) | -      |                                 |                 |                |                         |
| 139614   | A7V        | 157r        | 0.39        | 0.47\(\pm\)0.11               | 3.3            | 3\(\pm\)1        | S? S96,M01,D03         |
| 141569   | A0V        | 99          | 8.4\(\times\)10\(^{-3}\) | 0.07   |                                 |                 |                |                         |
| 142114   | B2.5V      | 132         | 7.5\(\times\)10\(^{-5}\) | 0.07   |                                 |                 |                |                         |
| 142165   | B5V        | 127         | 4.0\(\times\)10\(^{-5}\) | 0.064  |                                 |                 |                |                         |
| 142666   | A8V        | 116r        | 0.28        | 0.72\(\pm\)0.14               | -5.0           | 3\(\pm\)1        | S?(4.9). S96,M01,D03   |
| 143006   | G5V        | 82r         | 0.37        | 0.15\(\pm\)0.06               | -0.8           | -0.9\(\pm\)0.3   | S(0.95). J01,J96       |
| 143018   | B1V        | 140         | 1.5\(\times\)10\(^{-3}\) | 0.14   |                                 |                 |                |                         |
| 144432   | A9V        | 200         | 0.26        | 0.31\(\pm\)0.13               | -2.2           | 2\(\pm\)3        | D? S96,M01,D03         |
| 145718   | V718 Sco   | A8IV(6)     | 130         | 0.1    | 0.45\(\pm\)0.23               | -4.2           | -              | D? Marginal det. Z95,T01 |
| 150193   | A1V        | 150         | 0.15        | 0.07   |                                 |                 |                | Poss. ambient emission. M01 |
| 155826   | G0V        | 30          | 6.5\(\times\)10\(^{-4}\) | -      |                                 |                 |                | Bright ambient em. L02  |
| 163296   | A12V       | 122         | 0.16        | 4.3\(\pm\)0.13               | -6.4           | -4\(\pm\)1       | D. MS97,M01,J01        |
| 169142   | A5V        | 145r        | 0.1         | 1.7\(\pm\)0.13               | -3.1           | -3\(\pm\)2       | S(1.6). M01,D03        |
| 179218   | MWC614     | A0IV        | 243         | 0.62   | 0.6\(\pm\)0.12                | 16.1           | -3\(\pm\)5       | D. M01                  |
| 190073   | MWC325     | A2IV        | 400         | 0.4(5) | <0.08                         |                 |                |                         |
| 191089   | F5V        | 53          | 2.3\(\times\)10\(^{-3}\) | 0.25   |                                 |                 |                |                         |
| 212676   | B9V        | 670         | 4.7\(\times\)10\(^{-3}\) | 0.08   |                                 |                 |                |                         |
| 214953   | G0V        | 23          | 2.3\(\times\)10\(^{-4}\) | 0.28   |                                 |                 |                |                         |
| 216572   | A0IV(6)    | 590r        | 0.048       | 0.18\(\pm\)0.12               | 1.7            | 2.7\(\pm\)5      | Marginal detection. CWD98 |
| 224444   | B9IV(6)    | 300         | 8.7\(\times\)10\(^{-3}\) | 0.085  |                                 |                 |                |                         |
| 223344   | B9IV(6)    | 450         | 0.086       | 0.09   |                                 |                 |                |                         |
| 233517   | K5III      | 600r        | 0.057       | 0.21\(\pm\)0.11               | 36.0           | 46.5\(\pm\)1     | S(3.6). S01,F96        |
| 287841   | V346 Ori   | A2IV        | 400         | 0.1    | <0.06                         |                 |                |                         |
| 293782   | UX Ori     | A4IV        | 430         | 0.35   | 0.21\(\pm\)0.07               | 17.2           | 18.3           | S(0.98). CO at v=27. N01 |
| 344361   | WW Vul     | A2IV        | 370         | 0.42   | <0.95                         |                 |                | N01                     |
| -        | VX Cas     | A0V         | 760         | 0.3(5) | <0.09                         |                 |                |                         |
| -        | TW Hya     | K7e         | 56          | 0.3    | 2.16\(\pm\)0.2                | 12.35           | 12.6           | S. K97                  |

CO emission from discs around isolated HAeBe and Vega-excess stars
Notes to Table 1:

(1) Spectral types are either from Moro et al. (2001), from the references given, or from the Simbad database.
(2) Distances are normally from Hipparcos, except those marked ‘r’, which are taken from the given reference, or ‘v’ estimated from visual magnitude, uncorrected for reddening.
(3) Fraction excess is taken from the literature, or where not available, estimated from a fit to the SED (see text for details).
(4) Intensity units are main beam brightness temperature (using \( \eta_{\text{mb}} = 0.62 \)). To calculate the upper limits, the rms noise has been measured with 10 km s\(^{-1}\) channels; 1-\( \sigma \) values are given.
(5) Estimate of fractional excess is uncertain, due to wide range of temperatures in excess emission, possibly high extinction to star and/or incomplete wavelength coverage.
(6) Luminosity classification based on distance and optical magnitude.
(7) For targets with detected CO, an indication is given of whether the line is double-peaked (D) or single-peaked (S).

References:

B99: Beskrovnaya et al., (1999); CWD98: Coulson et al. (1998); D03: Dominik et al. (2003); DC98: Dunkin & Crawford (1998); F96: Fekel et al. (1996); G00: Greaves et al. (2000); J01: Jayawardhana et al. (2001); K02: Kalas et al. (2002); K97: Kastner et al. (1997); L02: Lisse et al., (2002); L03: Li & Lumine (2003); M98: Malfait et al., (1998); M01: Meeus et al. (2001); MS97: Mannings & Sargent (1997); MS00: Mannings & Sargent (2000); N01: Natta et al. (2001); PDK03: Piétu, Dutrey, Kahane (2003); S01: Simon et al. (2001); SD301: Sylvester, Dunkin & Barlow (2001); S96: Sylvester et al. (1996); SM00: Sylvester & Mannings (2000); T01: Thi et al. (2001); T04: Torres (2004); vdA98: van den Ancker et al. (1998); Z95: Zuckerman et al. (1995).

3 DETECTABILITY OF CO

A total of 59 targets were observed, of which 21 were detected in CO with 2 additional marginal detections (at the 2-\( \sigma \) level). In Fig. 1, we plot \( I_{CO} \), the measured CO intensity or 1-\( \sigma \) limit normalised to a distance of 100 pc, as a function of the fractional infrared excess \( f \). The normalisation of the CO line intensity assumes the emission to be smaller than the beam; the emitting regions are typically a few hundred au in radius (see below), which compares with the beam size of 1400 au at a distance of 100 pc. As the \( ^{12}\text{CO} \) line is likely to be optically thick (see below), the normalised CO intensity can be used to estimate a lower limit to the gas mass. Assuming optically thin emission and that the gas is in LTE, the total gas mass would be given by (e.g. Thi et al., 2001):

\[
M_g \approx 10^{-4}(T_{ex} + 0.89)/e^{16.02/T_{ex}} I_{CO}
\]

where \( T_{ex} \) is the excitation temperature, \( M_g \) the mass in units of Jupiter masses (\( M_J \)), the \( ^{12}\text{CO}/\text{H}_2 \) abundance ratio is assumed to be \( 5 \times 10^{-5} \) and \( I_{CO} \) is normalised to 100 pc (see above). Most emission arises from the outer regions of these objects, where the dust kinetic temperature, \( T_{dust} \), is between \( \sim 30 \text{K} \) (e.g. Beckwith & Sargent, 1993) and \( \sim 100 \text{K} \) (e.g. Dent et al., 2000). Assuming \( \text{H}_2 \) densities greater than \( 10^{10} \text{cm}^{-3} \), then the gas and dust are sufficiently coupled for \( T_{dust} \approx T_{ex} \). From eqn. (1), the likely range of temperatures will affect the derived mass limit by no more than a factor of 2 and so, adopting an excitation temperature of 60K, the horizontal line at \( I_{CO} = 0.1 \) on Fig. 1 corresponds to a minimum mass of \( 10^{-3} M_J \).

Also included in Fig. 1 are published limits to the \( J=2-1 \) CO emission from the Vega-excess stars Vega, \( \beta \) Pic, Fomalhaut and HR4796 (Dent et al., 1995; Liseau, 1999); we have assumed the same brightness temperature limits in both the \( J=3-2 \) and \( J=2-1 \) transitions.

The plot shows a clear link between the detectability of CO and a high fractional excess. We find 18 of the 27 objects with \( f \geq 0.1 \) are detected (upper right of the figure). Including the upper limits, the results indicate that 67 - 100 per cent of objects with \( f > 0.1 \) and 56 - 98 per cent of objects with \( f > 0.01 \) have significant CO emission (defined as where \( I_{CO}(D/100\text{pc})^2 \geq 0.1 \text{Kkm}^{-1} \)). The remaining stars with \( f < 0.01 \) are generally not detected in CO (only 2 or possibly 3 clear detections out of 27 objects with uncontaminated spectra). Ignoring the three very distant objects with poor scaled upper limits, this implies that \( \sim 8 - 20 \) per cent of low-excess objects (\( f < 0.01 \)) have \( I_{CO}(D/100\text{pc})^2 \geq 0.2 \text{Kkm}^{-1} \). However there are some notable exceptions to this general rule which are worth looking at individually.

HD98800 is the only star with \( f \geq 0.01 \) where the CO limit is significantly lower (\( f \geq 3\sigma \)) than all the others. As will be shown later, this indicates a relatively small limit to the surface area of circumstellar gas, although it may be linked to the fact that this is a quadruple system. Conversely, there are two (possibly three) discs with low \( f \) (<0.01) which have relatively bright CO emission: HD141569, which has a clear double-peaked line and a scattered light disc, HD9672 (also double-peaked) and HD4881. These will be discussed individually later sections.

For a reprocessing disc viewed near face-on, the infrared excess is approximately the fraction of stellar radiation intercepted by the disc. To first order this is the effective solid angle subtended by the disc as seen from the star so, assuming a disc of constant opening angle \( \theta \), and mean optical depth through the disc to optical stellar photons of \( \tau_{V} \), the excess \( f \) is given by (e.g. Backman & Paerels, 1993):

\[
f = (1 - e^{-\tau_V}) \sin(\theta/2)
\]  (2)

In a typical photodissociation region, CO can survive at \( \lambda V \geq 2-6 \) (Hollenbach et al., 1991). As \( \tau_V \sim \lambda V \), then assuming that photons from the central star are the dominant cause of CO dissociation (van Zadelhoff et al., 2003), we can estimate the disc opening angle required for significant CO to be present. The results of this survey imply that >67 per cent of discs of opening angle \( \geq 12^\circ \) (\( f \geq 0.1 \)) will have gas masses \( \geq 10^{-3} M_J \). Including the upper limits and ignoring the quadruple system HD98800, the results are consistent with all discs of \( f \geq 0.01 \), or \( \theta \geq 1^\circ \), having at least \( 10^{-3} M_J \) of molecular gas.

The low extinction along the line of sight towards the stars with detected circumstellar CO (typically \( \lambda V \sim 1 \) mag;
Figure 1. Integrated CO intensity for target stars ($T_{mb} dv$, in units of K km s$^{-1}$) normalised to a distance of 100 pc, plotted against the fractional excess of continuum emission above that of the stellar photosphere. Objects with clear CO detections are depicted as filled circles and those with uncertain identifications as open circles; the 1-$\sigma$ upper limits of the remainder are also shown. Also included are published CO upper limits of nearby archetypical Vega excess stars (Dent et al., 1995; Liseau, 1999); these are shown as upper limits with a cross. The horizontal dashed line represents a minimum gas mass of $10^{-3} M_J$, and vertical line represents the critical excess for CO emission (see text for details).

van den Ancker et al., 1998) means we are unlikely to be looking through the disc itself, so the inclination $i < (90 - \theta/2)$. Assuming the sample of discs is randomly-oriented on the sky, the mean inclination would be 60$^\circ$, giving a mean opening angle $\theta$ of $<30^\circ$. For realistic discs, the photons may be intercepted at an inner hot bulge (e.g. Natta et al., 2001) rather than an outer flaring region, although either structure would result in an increase in the total excess $f$, as well as shielding more distant gas in the disc from UV photodissociation; as a result the above relation would still apply.

The gas discs with the lowest $f$ are HD141569, HD4881 and HD9672; from eqn. 1, their opening angles range from $\sim 1^\circ$ down to as small as 0.1$^\circ$. There is no evidence for strong near-infrared excesses in these stars (e.g. Sylvester et al., 1986) as predicted by the hot inner bulge models, which would suggest the optically thick regions of their discs have relatively large radii as well as being physically thin. Such structures are even thinner than the opening angle of 7$^\circ$ seen in the edge-on $\beta$ Pictoris dust disc (Heap et al., 2000), and the detections of CO imply it can also exist in such thin layers.

4 SPECTRAL PROFILES

Emission from CO around five of the brightest isolated HAeBe stars have been resolved with interferometers (Mannings & Sargent, 1998, 2000; Piétu et al., 2003; Augereau et al., 2004). In all cases the material appears to be located in Keplerian discs with outer radii of a few hundred au; however the angular sizes are often only marginally larger than the existing interferometer beam sizes.

The CO emission intensity from most of the objects in
The density is assumed to be zero for \( r < R_{in} \) and \( r > R_{out} \), and \( n_0 \) and \( r_0 \) are scaling factors for the total disc mass, obtained from the dust mass assuming a constant gas:dust ratio of 100. Dust masses are obtained from the literature, mostly from fits to the continuum SED. The narrow features in several of the spectra suggests that the effect of turbulent line broadening is negligible; consequently only thermal broadening is included (see also Beckwith & Sargent; Piétu et al., 2003). The model assumes a constant gas:dust ratio without the effects of chemistry; Aikawa & Herbst (2001) indicate that chemical reactions in the disc do not significantly alter typical emergent lines profiles of molecules such as \(^{12}\)CO, as the emission is so optically thick. However, the CO abundance can be affected by the local UV photoionisation rate, which depends on distance and extinction to the star and the stellar spectral type, as well as the interstellar radiation field and optical depth to the surface of the disc. The stellar photodissociation is based on an analytical fit to the model of Hollenbach et al. (1991). Interstellar photodissociation is approximated by effectively removing emission from the disc surface down to \( \Lambda_V = 3 \) mag. However, in most cases the density is sufficiently high that the UV has little effect on the CO abundance throughout most of the disc volume.

As the mean densities for most discs under investigation are typically \( > > 10^4 \) cm\(^{-3} \), then the gas and dust will be in thermal equilibrium; the dust temperature is assumed to be that of small grains radiatively heated the star (e.g. Aikawa & Herbst, 2001). The excitation temperature is then given by:

\[
T_{ex} = 282 \left( \frac{L}{L_c} \right)^{0.2} \left( \frac{f}{f_B} \right)^{-0.4} \left( \frac{R}{1 \text{au}} \right)^{-0.2}
\]  

(5)

Smaller grains, such as classical ISM dust, will be hotter, but offsetting this is the possibility that the outer disc may be shielded from the star by the inner regions and so would be cooler. The extinction to the star depends on the flaring angle and detailed structure of the inner disc; for a flared disc for example, the dust higher above the disc plane will be hotter. The effective CO excitation temperature at a particular radius is approximately that at the \( \tau = 1 \) surface (van Zadelhoff et al., 2001). The height of this surface above the disc plane depends on \( \theta \) and the inclination angle \( i \) as well as the disc structure. In the case of a face-on disc, comparison of the temperatures at the \( \tau = 1 \) surface (see van Zadelhoff et al., 2001, their Figure 6) with the temperatures assumed in our present model indicates that we may be underestimating the temperature at a given radius by a factor of between 1.0 and 2.0. For more inclined discs, however, we will see deeper into the gas, and so the temperature at the \( \tau = 1 \) surface will actually be lower. This suggests that the uncertainty in \( T_{ex} \) is less than a factor of 2; for unresolved discs in an optically thick line, this implies the disc radius would then be in error by a factor of \( \leq 1.5 \), which gives some indication of the possible uncertainty of \( R_{out} \).

4.2 Line profile fitting

The spectra of the targets with significant detections of CO are shown in Figure 2, along with the best fit models. Table 2 summarises the modelling results for these objects; also given is the derived disc angular diameter. In some cases the
parameters are not well constrained because of the low s:n of the data - this is indicated in the table. Dust masses marked (1) are scaled to the adopted distances. Lines with a clear double-peaked profile are identified by ‘D’.

In most cases, the CO profiles can be fitted reasonably well by the simple disc model by a suitable choice of $r$ and $R_{out}$. As the line emission is generally optically thick from all regions of the disc, the disc outer radius determines the intensity to first order, and the disc inclination mainly affects the overall line width. The inner radius is constrained by the line wings although, apart from the closest objects, beam dilution of emission from this compact region means $R_{in}$ is not well constrained. The opening angle $\theta$ has a small effect on the line intensity and shape at the lower relative velocities, although in most cases we cannot constrain it, and have simply set it to a fixed value.

The spectra from nine objects listed in Table 2 have clear double-peaked spectra consistent with a disc. Another nine objects have single-peaked lines, although only a small number of these (HD4881, HD143006 and UX Ori) have narrow line widths more consistent with ambient cloud emission (< 1 km s$^{-1}$). The remaining have more ambiguous line profiles (CQ Tau, HD139614, HD144432, HD145718), although all are relatively broad suggesting they arise from a disc rather than an ambient cloud. Apart from HD179218 and HD233517, the stellar velocities, if known, agree with those of the CO, confirming the gas is associated with the stars. Assuming all the single-peaked profiles arise from discs viewed almost face-on, then the average outer radii of these objects is 110 au, compared with 170 au for the double-peaked and broad spectra; the similarity of these values also suggests a common origin for all emission. In the following sections, we discuss the results for individual objects.

4.2.1 HD9672

HD9672 (49 Cet) is one of only three debris discs with $f > 10^{-3}$ (e.g. Jayawardhana et al., 2001), the other two being HR4796 and $\beta$ Pictoris. A weak CO line was detected by Zuckerman et al. (1995), making this not only the only bona-fide debris disc with detectable CO, but also one of the closest gas-rich discs (only TW Hya is closer). Fig. 2a confirms the emission centroid lies close to the stellar velocity (9.86 km s$^{-1}$) and shows the line profile to be double-peaked.

Weinberger et al. (1999) saw no evidence of scattered light at radii beyond 1.6 arcsec (~100 au), although Jayawardhana et al. (2001) did detect mid-infrared emission extending to a radius of ~50 au. The relatively weak CO line brightness implies the emission region likely has a small surface area. The data are consistent with a compact disc (outer radius ~17 au) inclined at 16$^\circ$. The relatively high velocity wings imply gas is present at radii ≤5 au. A more inclined ring (i ~ 35$^\circ$) of radius 50 au (equal to that seen in the mid-infrared) would produce a similar separation of the line peaks but does not reproduce the higher velocity wings (see dashed line on the spectrum in Fig. 2a).

4.2.2 AB Aur

A disc was resolved around this star using mm-wave interferometry in the J=1-0 $^{13}$CO line (Mannings & Sargent, 1997). The beam size was 4-5 arcsec (~720 au) and the derived outer radius was 450 au. HST images show a scattering disc extending to a radius of ~8 arcsec (Grady et al., 1999), and an extended arc of dust at $r \sim 10–20$ arcsec, likely due to remnant ambient gas. Grady et al. suggest that the disc is almost face-on (i < 45$^\circ$), and may be flared, judging by the radial emission profile.

Our fit using an outer radius of 600 au (Fig. 2a) shows reasonable agreement with the spectrum at low relative velocities. Notably, the narrow linewidth implies that the disc must be almost face-on ($i \sim 12^\circ$), agreeing with the symmetrical optical image, rather than the higher inclination derived from the interferometer map. But this simple model cannot explain the line wings seen out to relative velocities of ±2 km s$^{-1}$. This implies that either the inclination of the inner region of the disc is higher (a model with $i = 17^\circ$, $i \sim 300$ au can fit the profile of the wings alone, and is shown by the dashed line in Fig. 2a), the low-velocity emission is dominated by ambient gas, or there is an additional higher-velocity component such as a molecular outflow. The presence of highly extended, possibly ambient material in the scattered light images suggests that the narrow central component in the $^{13}$CO line may not be from the disc itself; consequently $i = 17^\circ$ and $R_{out} \sim 300$ au may represent the true values of the circumstellar disc.

4.2.3 MWC480

This disc has been resolved in J=2-1 CO using interferometry with a 1.8 arcsec beam (Mannings et al., 1997). By comparing with a two-component Gaussian model of surface brightness, they derived an outer cutoff of ~650 au (after scaling to the distance in Table 1). However, our data (Fig. 2a) are consistent with a disc model with outer radius ~245 au; the reason for this discrepancy is thought to be differences in the model and possibly the increased sensitivity of their J=2-1 data to extended lower-density extended regions.

In addition to the double-peaked shape, two other features in the deep CO spectrum are worthy of note. One is that emission is detected out to relative velocities of ±3.5 km s$^{-1}$, implying the gas disc has an inner radius smaller than 20 au. The second is that the line profile is clearly asymmetrical; a similar asymmetry was seen in the reconstructed interferometric spectrum of J=2-1 $^{13}$CO in Mannings et al. and the $^{13}$CO single-dish spectrum in Thi et al. (2004), although the s:n of both of these spectra are lower than shown in Fig. 2a. A possible explanation is that the asymmetry is due to systematic telescope pointing offsets. With a 14 arcsec Gaussian beam, the observed 30 per cent difference in intensities of the two peaks in Fig. 2a would require a consistent pointing offset of 5 arcsec along the disc plane. Not only is this significantly larger than normal telescope pointing errors, but also the data were taken from runs on several different nights with consistent results. We have instead attempted to fit this asymmetry by imposing a sinusoidal azimuthal deviation in either the density or temperature around the disc. As the CO emission is optically thick over most of the disc, implausibly large deviations in density of ≥99 per cent are necessary to explain the asymmetric spectra. However, the peak-to-peak temperature difference required to match the line profile is 30 per cent. The or-
Figure 2. (a-d) Spectra of J=3-2 $^{12}$CO for the objects where emission was detected (histogram). Also shown are the best fit models (solid line); in some cases an alternative model is shown by the dashed lines - see discussion of individual objects for details. Model parameters are given in Table 2 and described in more detail in the text for individual objects. Velocity scale is km s$^{-1}$ (Heliocentric reference), and intensity unit is main beam brightness temperature (K); note that the ranges on the axes vary from source to source.

This asymmetry needs further confirmation with high s:n data in other molecular lines, along with more detailed modelling including a fuller treatment of dust temperature and structure throughout the disc.

4.2.4 HD34282

A detailed model has been derived from interferometric data by Piétu et al. (2003), including a revision to the distance and hence the luminosity of this star (see Table 1). The results from fitting our single-dish spectrum give an inclination consistent with their data, although the outer radius from our fitting is 360 au, a factor of ∼2 smaller than theirs. The peak line brightness in Fig. 2a is 0.3K; if the disc is optically thick with a mean brightness temperature of 30K, this would suggest a beam filling factor of 1 per cent and hence a radius of ∼300au, more consistent with the current model.
4.2.5 CQ Tau

This object is thought to be a UX Ori star, suggesting the disc is viewed close to edge-on, and an inclination of $66^\circ$ was estimated based on a model of the variability by Natta & Whitney (2000). An upper limit to the gaseous disc radius of 85 au was measured using interferometry (Mannings & Sargent, 2000), although Testi et al. (2003) resolved the dust continuum emission at 7mm, finding a radius of 100-200 au. The single-dish CO spectrum shows a relatively broad but weak line (Fig. 2b), which can be fitted with a contiguous disc of outer radius 30 au (inner radius $\leq 10$ au) and inclination $14^\circ$ (the solid line in the figure). But this inclination is inconsistent with previous estimates based on the variability. A larger, thin and somewhat more inclined ring model would fit the observed brightness temperature and width of

the line core, and be consistent with the maximum dust radius ($R_{\text{ext}} = 80$ au, $R_{\text{in}} = 70$ au, $i = 30^\circ$, $\theta = 2^\circ$; see dashed line in Fig. 2b). However, there is weak evidence of broad line wings, which are not reproduced by such a thin ring; furthermore a ring with an inclination as high as $66^\circ$ would be inconsistent with the narrow CO line and compact size from interferometry. To reconcile this difference, the system could contain a compact gas disc or ring with low inclination, but with a highly flared dust disc; alternatively the gas lies in a more extended ring, but the line brightness is low because of CO depletion and excitation conditions in the disc atmosphere, which have not been included in the present model.
4.2.6 HD135344

This is the one of the closest gas-rich discs to the Sun (CWD98), and also the oldest known star with such a disc: Thi et al. (2001) derive an age of 16.7 Myr. No scattered light has been detected using coronograph observations down to radii of $\sim 1$ arcsec although a binary pair was found at separation $\sim 5.8$ arcsec (490 au) from the primary (Augereau et al., 2001). The CO line is double-peaked (Fig. 2b) and can be well fitted by a compact disc of outer radius 75 au viewed nearly face-on. A more extended edge-on ring is excluded by the presence of wings in the line profile. If we assume the nearby binary pair are associated with HD135344, this would imply an upper limit of $\sim 200$ au to the disc radius, as material is unlikely to exist in a stable orbit at radii within a factor of $\sim 2$ of the binary separation.

4.2.7 HD141569

An extended region of scattered light from a circumstellar disc has been imaged by several authors using coronography (e.g. Mouillet et al., 2001, and refs. therein), and both this and mid-infrared images indicate an inclination of 52$^\circ$. In addition, CO emission was detected from this object by Zuckerman et al. (1995), and recently imaged using interferometry (Augereau et al., 2004). We obtained a deep CO spectrum (Fig. 2b), which shows a double-peaked line profile, with a distinctive “shoulder” at higher relative velocities. A single ring or disc structure cannot explain this line-
Table 2. Stars with CO detections: best fit model parameters.

| Star         | Dust mass ($M_\odot$) | $R_{in}$ (au) | $R_{out}$ (au) | $D_{out}$ (arcsec) | $i$     | $\theta$ | Notes(2)                                                                 |
|--------------|------------------------|--------------|---------------|-------------------|---------|----------|--------------------------------------------------------------------------|
| HD4881       | $3.9 \times 10^{-5}$   | -            | 35            | 0.4               | $\leq 5$ | $\leq 10$ |                                                                           |
| HD90672      | $4 \times 10^{-6}$     | $<5$         | 17$\pm$5      | 0.6               | 16$\pm$3 | 10       | D                                                                        |
| AB Aur       | $2.1 \times 10^{-4}$   | $\leq 50$    | 600$\pm$50    | 8.4               | 12$\pm$2 | 5        | D; Poss. 300au inner disc - see text                                     |
| MWC480       | $2.0 \times 10^{-4}$   | $\leq 20$    | 245$\pm$30    | 3.8               | 28$\pm$2 | 10       | D                                                                        |
| HD34282      | $1.1 \times 10^{-3}$   | $\leq 50$    | 380$\pm$20    | 1.8               | 50$\pm$5 | 10       | D                                                                        |
| HD35700      | $2.1 \times 10^{-5}$   | $\leq 30$    | 80$\pm$10     | 1.3               | 25$\pm$2 | 10       | D                                                                        |
| HD36112      | $2.9 \times 10^{-4}$   | -            | 170$\pm$30    | 1.7               | $\leq 10$ | 10       | Single broad line                                                        |
| CQ Tau       | $2.2 \times 10^{-4}$   | $\leq 10$    | 30$\pm$5      | 0.7               | 14      | 10       | Broad line                                                               |
| HD38120      | $10^{-5}$              | -            | 300$\pm$50    | 1.2               | $<8$    | 10       |                                                                           |
| HD135344     | $10^{-4}$              | $\leq 10$    | 75$\pm$5      | 1.8               | 11$\pm$2 | 10       | D                                                                        |
| HD139614     | $10^{-4}$              | $\leq 20$    | 110$\pm$3     | 1.4               | $\leq 10$ | 10       |                                                                           |
| HD141569     | $10^{-5}$              | 90$\pm$5     | 250$\pm$2     | 5.0               | 52      | 0.5      | D; Double ring structure - see text                                      |
| HD142666     | $3 \times 10^{-4}$     | -            | 45$\pm$10     | 0.8               | 18$\pm$5 | 10       | Single broad line                                                        |
| HD143006     | $1.6 \times 10^{-5}$   | -            | 35$\pm$5      | 0.8               | $\leq 3$ | 10       |                                                                           |
| HD144432     | $2 \times 10^{-3}$     | -            | 60$\pm$20     | 0.6               | 48$\pm$10 | 10       | Low s:n; broad line?                                                     |
| HD145718     | $4.5 \times 10^{-5}$   | -            | 60$\pm$30     | 0.9               | 32$\pm$10 | 10       | Low s:n                                                                 |
| HD163296     | $5 \times 10^{-4}$     | $\leq 20$    | 245$\pm$20    | 4.0               | 30$\pm$2 | $\leq 10$ | D                                                                        |
| HD169142     | $10^{-3}$              | -            | 130$\pm$10    | 1.8               | $\leq 5$ | 10       |                                                                           |
| HD179218     | $10^{-4}$              | -            | 120$\pm$20    | 1.9               | 40$\pm$10 | 10       | D; Stellar and CO velocity differ                                        |
| HD186571     | $1.7 \times 10^{-4}$   | -            | -             | -                 | -       | -        | Stellar and CO velocity differ                                           |
| UX Ori       | $4.2 \times 10^{-4}$   | -            | 95            | 0.4               | $\leq 8$ | 10       | Additional ambient gas component                                         |
| TW Hya       | $3.0 \times 10^{-4}$   | $\leq 30$    | 160$\pm$10    | 5.7               | 5$\pm$2 | $\leq 10$ |                                                                           |
shape, giving for example, the model shown by the dashed line in Fig. 2b. Instead we adopted a double ring structure. The inclination of the dust disc is well constrained by the images so we adopt the same value for the gas. The relatively narrow overall line width indicates ring radii of 95 and ∼250 au (shown by the solid line on Fig.2b). The latter is similar to the radius found in the recent interferometry results. The low disc mass and high UV luminosity of the star requires the rings to be physically thin in order to maintain high extinction and avoid photodissociating the CO. The best fit to the data has an opening angle with the innermost edge of our inner CO ring.

A further feature of the spectrum in Fig. 2b is the asymmetry of the narrow component; at positive velocities the line is ∼50 per cent brighter than at negative velocities. As noted for MWC480 above, if the CO emission is optically thick, this would require a large variation in density within the ring (or a smaller variation in temperature). In the case of HD141569, a large variation in CO density could be explained by a difference in the extinction to the star (and hence differences in photodissociation rate). A recent K-band image (Boccaletti et al., 2003) also shows an asymmetry in scattered light, whereby the north-eastern sector of the 200 au ring is significantly brighter. If this is related to the CO asymmetry, it would indicate this is the side of the ring approaching us.

Overall the CO model of HD141569 suggests that molecular gas and dust is well intermixed in a physically thin pair of rings. A more detailed comparison between the scattering dust and molecular gas would require a high resolution CO map of this complex system.

4.2.8 HD163296

The disc around this star has been resolved both in scattered light and mm-wave interferometry (Mannings & Sargent, 1997; Grady et al., 2000). Our high spn spectrum shows reasonable agreement with a model disc inclined at 30° (Fig. 2c), although the deep dip near the stellar systemic velocity cannot be reproduced in a simple model. One possible explanation for this might be self-absorption from cool foreground gas, although the low optical extinction to the star suggests little material exists along the line of sight (van den Ancker et al., 1998). The CO spectra of Thi et al. (2004) shows line-of-sight gas at velocities considerably different from that of the star (and outside the range shown in Fig. 2c); however, there is no evidence of extended emission at the stellar velocity itself. The derived disc inclination is inconsistent with that found from the morphology of the interferometric map - we cannot reproduce the line profile with inclinations as high as 60°. However, the derived outer radius is in close agreement with the interferometric result, and is similar to the inner edge of the dark lane seen in scattered light, indicating that the gas and dust co-exist within the disc. Modelling the CO emission profile out to relative velocities of ±4km s⁻¹ suggests that gas exists in the disc down to radii less than 20 au. No additional high-velocity molecular outflow component is needed to explain the line shape.

4.2.9 UX Ori

Extended CO emission is seen in this region at v∼27km s⁻¹ in both the signal and reference positions, however, a narrow emission line was also seen at the stellar velocity itself (Fig. 2d). All model fits which assume the emission is from a disc require an orientation close to face-on (i ≤ 20°) to reproduce the line width. This is inconsistent with the interpretation of the variability as obscuration in a near edge-on disc (Natta et al., 1999). The line may instead be from ambient gas more distant from the star, possibly associated with the extended far-infrared emission seen by Natta et al.; mapping of this emission would help identify its origin.

4.2.10 TW Hya

We obtained a deep CO spectrum of disc around the 8 Myr old star TW Hya, known to have numerous emission lines at sub-mm wavelengths (e.g. van Zadelhoff et al., 2001). Although TW Hya is a K7 rather than an AeBe star, the disc is well known to be close to face-on (i ≤ 20°) and a physically thin disc (van Zadelhoff et al., 2000) do not significantly affect the derived result; for such a depletion, the disc size required to fit the present data increases only slightly (190 au), confirming that the emission is indeed extremely optically thick.

The narrow line width seen in Fig. 2d indicates an inclination of only i ∼ 5° and a physically thin disc (6 ∼ 5°). However, weak wings reaching to ±1.3km s⁻¹ can be seen in the deep spectrum. These require a model where the gas disc extends in to a radius <30 au (for comparison, a model with a central hole of radius 50 au gives the spectrum shown by the dashed line). This compares with the innermost edge of the dust disc and the developing gap (4 au) derived by Calvet et al. from the continuum SED.
5 DISCUSSION

5.1 Disc outer radii

The outer disc radii derived in our sample of stars mostly lie between 30 and 400 au, with a mean of \( \sim 150 \) au. Most are larger than the solar system (\( \sim 50 \) au to the edge of the Kuiper Belt), and are closer to the size of the debris discs seen around older stars (typically 50 - 150 au, e.g. Holland et al., 1998). However, as many as 5 of the gas discs are compact (\( R_{\text{out}} \leq 50 \) au), and at least another 7 have evidence of gas at inner radii smaller than 50 au. So what determines the radius, and how is the gas removed?

Figure 3 shows that the disc size is not correlated with the stellar spectral type, with a Pearson correlation coefficient of -0.04. This applies over 2.5 orders of magnitude in luminosity. We also include published T Tauri disc radii from Simon et al. (2000) as well as model fits to the CO upper limits for stars in Table 1 with \( f \geq 0.1 \), ie which are predicted to have measurable CO emission (see discussion above).

Figure 3 also shows the radius at which a black body in thermal equilibrium with the central star reaches the CO freeze-out temperature (assumed to be 20K). This assumption of black body temperature would require large grain sizes (> 1mm), as well as low extinction to the star. It is likely that the disc mid-plane temperature would be lower than this in some objects due to the high extinction. Conversely, if the grain sizes were closer to those in the interstellar medium (ie little grain growth had occurred) the temperature would be higher. If freeze-out were important, we would not expect to see disc radii above this line. Fig. 3 shows that this is indeed the case for all stars of type F or earlier. However, some T Tauri stars lie above this line, suggesting that another source of energy such as accretion luminosity may be heating these discs.

5.2 Comparison with dust discs

The continuum SEDs from many of the objects in Table 2 have been used to derive disc sizes, based on standard dust models (e.g. Dominik et al., 2003). In all cases except HD135344, the SED-derived radii are smaller than those derived from CO; we attribute this to the greater sensitivity of the J=3-2 transition of CO to a given mass of material. However, it is possible that large grains could accrete rapidly through a disc, leaving a gas disc larger than the dust disc (Takeuchi & Lin, 2002).

We can also compare the total disc mass (derived from the continuum SED, scaled assuming a constant gas:dust ratio of 100) with the gas disc outer radius (Fig. 4). There is some evidence of a correlation between the disc size and mass, with a Pearson correlation coefficient of 0.62. The slope of the fit is 2.8, close to a value of 3 which would apply if the mean density in the discs was constant. Further data over a wider range of masses would be needed to confirm this result.

Scattered light from dust around four discs in Table 2 has been detected using coronography (AB Aur, HD141569, HD163296 and TW Hya). These are all predicted from the CO modelling to have angular sizes > 3 arcsec. Their optical sizes and distributions are similar to those derived from CO.
implying that the gas and small scattering dust grains are closely intermixed. The predicted angular size of MWC480 also suggests that scattered light may be detectable, however, coronograph imaging has not shown extended emission (Augereau et al., 2001). One possible explanation is that this disc is not flared, or is shadowed by a thick inner disc.

5.3 Gas disc lifetimes

Many authors have used disc masses derived from mm-wavelength continuum or line fluxes to estimate the disc lifetime (e.g. Beckwith et al., 1990; Thi et al., 2001), and the results suggest that dust discs survive for typically \( \sim 10^5 \) yr. However, mass estimates are uncertain because the detectable dust is part of a broad grain size distribution and so represents only a small fraction of the total solid mass. The gas:dust ratio is also uncertain (e.g. Thi et al., 2001), and is likely to evolve in these discs. Rather surprisingly, the results show no evidence of evolution of disc mass between ages of \( 10^7 \) and \( 10^7 \) yr, around either T Tauri (Beckwith et al., 1990) or HAeBe stars (Natta et al., 2000).

Although we cannot derive gas masses from \(^{12}\)CO (see above), we can use the results to see whether there is an evolution in size of the gas disc; this is illustrated in Figure 5. Typical uncertainties in the age derivations are 1-3 Myr, and dominate the plot. However, splitting the sample in two based on their age, the discs around older objects (7-20 Myr) have a mean radius of 75 au, significantly smaller than the younger discs (3-7 Myr), where the mean radius is 210 au. There are no large, old gas discs (which would appear in the top right of the figure). This effect is strengthened further if the published results from relatively young (1-5 Myr) T Tauri discs are included. Although these have significantly lower luminosity, the lack of dependence of size with spectral type (see Fig. 3) indicates that disc age is more important than stellar luminosity. Discs around even younger stars (Class I or II YSOs, typically of age 0.1-1 Myr) are difficult to separate from surrounding ambient clouds, both observationally and in the definition of where the disc ends and “ambient” gas begins. Fuente et al. (2002) found that the very large-scale (\( \sim 10^6\)au) ambient gas around HAeBe stars disappears by \( \sim 1\)Myr. However interferometric observations show discs with radii of a few \( 10^2 \) to \( 10^3\)au around some Class I stars, thought to be \( \leq 1\)Myr in age (e.g. Mundy et al., 2000). Overall Fig. 5 shows evidence for evolution of the gas disc size, such that \( R_{\text{max}} \) decreases by a factor of \( \sim 3 \) over the 3-20 Myr period. An alternative view is that the lifetime of the outer \( \sim 200\)au gas disc region is \( \sim 7\)Myr, and the inner \( \sim 75\)au region is \( \sim 20\)Myr. However, this result should be treated with caution, as the age determinations are somewhat uncertain.

Models of disc removal suggest that timescales should increase with radius (e.g. Hollenbach et al., 2000). So we might expect relatively little evolution of the outer radius except at the end of the disc lifetime, when the gas rapidly disappears (Clarke et al., 2002) or the obscuring dust coagulates, allowing photodissociation of the outer regions. However, the dominant removal mechanism in the outer (100-1000 au) region of the disc may be external photoevaporation (Matsuyama et al., 2003) or interaction with other stars in a young cluster (Mundy et al., 2000). The decrease in mean outer radius in Fig. 5 would therefore be determined by interaction with the local environment, rather than evolution of the star itself.

Finally the results of the modelling indicate that at least \( 10^{21}\)kg of gaseous CO exists for \( \sim 20 \) Myr at radii \( \leq 100\)au around these stars. This could be available to form \( \sim 10^8 \) 1km-sized comets, assuming a cometary CO mass fraction of 10 per cent.

6 CONCLUSIONS

We have surveyed a sample of 59 isolated HAeBe stars and Vega-excess stars for sub-mm \(^{12}\)CO emission. A clear correlation with fractional excess is seen, with a high CO detection rate around stars with \( f \geq 0.1 \) (18/27) and a low detection rate for those with \( f < 0.01 \) (2/27). This is explainable by CO dissociation by stellar UV photons; the stars showing high \( f \) have an optically thick disc shielding the gas. Most discs with detected CO have derived opening angles \( \geq 12^\circ \), although in the low-\( f \) objects, the shielding disc must be geometrically thin (\( \theta \leq 1^\circ \)). The data are consistent with all of the \( f > 0.1 \) discs having significant gas (with a minimum mass of \( 10^{-3}\)M\(_J\)), suggesting that CO will exist as long as it is sufficiently shielded from stellar UV.

Approximately 50 per cent of the CO lines are double-peaked, which we interpret as arising in a Keplerian disc. Comparing a basic model with the CO profiles, we derive outer radii of 20-300 au for the majority of the discs. In most cases these radii are considerably greater than those
CO emission from discs around isolated HAeBe and Vega-excess stars

derived from continuum SED modelling. These gas-rich isolated discs are found around stars of ages from 3-17 Myr, and spectral types K through to B9. There is no dependence of size with the spectral type. But there is evidence of a correlation between radius and disc mass, with $M_d \propto R_{out}^8$. Also the outer radius is dependent on disc age: splitting the stars into two age groups, we find stars $< 7$ Myr in age have discs $3$ times larger than those of age $7-20$ Myr. The results indicate that gas-rich discs are available to form planets and may last a factor of two longer in the inner $\sim 75$ au region.

In the four largest CO discs, published scattered light images show comparable dust and gas outer radii, suggesting that the scattering dust and molecular gas are co-located within these discs. In only one case (HD141569) is there evidence of a central gas-free region; many of the others show evidence that gas is found down to radii smaller than 30au.

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