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How to cite:

Richardson, K. J.; White, Glenn J.; Avery, L. W. and Woodsworth, A. W. (1987). Submillimetre CO observations of the Cepheus A outflow. *Astronomy & Astrophysics*, 174(1-2) pp. 197–202.

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Submillimetre CO observations of the Cepheus A outflow

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Received June 13, accepted September 10, 1986

Summary. We have carried out spectral mapping of the Cep A region in the $J = 3 - 2$ transition of CO. The high velocity wings symptomatic of outflowing gas are evident over a region $\sim 6 \times 6$ arc min in extent ($\sim 1.3 \times 1.3$ pc). There appear to be 2 outflows, as found also for HCO⁺ by Loren et al. (1985). The CO $J = 3 - 2$ red wing intensity is enhanced relative both to lower transition CO data and to HCO⁺ $J = 1 - 0$, particularly to the south and east of Cep A, a result which suggests the presence of hot, optically thin gas in the flow. No such significant enhancement is seen, however, in the blue wing. The data are discussed in terms of a 2 component outflow in which the HCO⁺ emission originates mainly from dense clumps in the flow while a less dense (but $> 4 \cdot 10^4 \text{ cm}^{-3}$) interclump medium is responsible for most of the ¹²CO emission.

Key words: molecular clouds – interstellar molecules

1. Introduction

Cepheus A is a dense core in the star formation region Cep OB3 (Sargent 1977). It has been shown to be a molecular outflow source (Rodriguez et al. 1980) and has subsequently been extensively observed at various spatial resolutions in the $J = 1 - 0$ transition of CO (Bally and Lada, 1983; Loren, 1981; Ho, et al. 1982; Hayashi et al. 1985a). It has in addition been observed (though less extensively) in the CO $J = 2 - 1$ transition (Plambeck, et al., 1983; Levreault, 1985; Loren, et al., 1981; Margulis and Lada, 1985). The core region has been mapped in the infrared and submillimetre continuum by Beichman et al. (1979) and by Evans et al. (1981). From the continuum observations, a total source luminosity of $\sim 2.5 \cdot 10^4 L_{\odot}$ was derived. VLA observations at 6 cm by Hughes and Wouterloot (1984) revealed 14 continuum sources within a central area of $\sim 30 \times 40$ arcsec, each of which, they suggested, could be excited by a star. However, Torrelles et al. (1985) concluded that most of these were more likely to be bright radio rims, and that the region's total luminosity could be accounted for by 2 B1 ZAMS stars situated close to or at the positions of H₂O maser emission (Lada et al., 1981; Cohen et al., 1984). Recent high resolution molecular line mapping in lines of CS (Hayashi et al., 1985b), HCN (Weliachew et al., 1986) and NH₃ (Torrelles et al., 1985; Torrelles et al., 1986) reveal a central

dense disk, with considerable clumpy structure, which lies at the centre of the outflow, and upon which it may exert a constraining influence. A group of Herbig Haro objects and a radio continuum peak lie ~ 2 arc min west of Cep A, close to a group of optical nebulae GGD 37 (Gyulbudaghian et al., 1978; Hartigan and Lada, 1985). From CO and HCO⁺ observations, Loren et al. (1984) have suggested that a second, less energetic, molecular outflow may be present close to these objects.

Much of the recent work on Cep A has been devoted to achieving more detailed mapping of the central square arc minute at a variety of wavelengths, using high spatial resolutions. To complement such work, and to provide a comparison with the published lower CO transition mapping of this source, we have obtained a spectral map in the CO $J = 3 - 2$ line, over a region $\sim 4 \times 6$ arcmin in extent. This was carried out with the aim of investigating the large scale structure of the outflow region, which the previously reported data have shown to be complex.

2. Observations

The CO $J = 3 - 2$ data at 345.796 GHz were obtained over the period 1983 October 15–20 with the Canada-France Hawaii Telescope (CFHT) on Mauna Kea, Hawaii. The receiver used was the Queen Mary College InSb submillimetre heterodyne system (White et al., 1986), which achieved a typical system noise temperature, including atmospheric and telescope losses, of 300–400 K. The beam size (FWHM) was 1 arc min. Pointing was checked regularly against nearby stars and is believed to be correct to within a few arc seconds. Calibration was carried out at 15–20 min intervals using the standard chopper wheel method, and the data are presented in terms of the quantity T_r^* , with the forward spill-over efficiency factor η_{fss} being estimated as 0.8. (For details of this calibration method and definitions of the above quantities, see Kutner and Ulich, 1981). The spectra presented in this paper represent typically 4–8 min integration on each sky position, during which the klystron local oscillator was scanned in frequency across the spectrum, giving a total of 4–8 sec integration per 1 km s^{-1} wide velocity channel.

3. Data

The spectra obtained over the region are shown in Fig. 1. The self-reversal already reported in lower CO transitions is prominent also in the $J = 3 - 2$ line, and is present over most of the region mapped, but tends to disappear towards the edges of the

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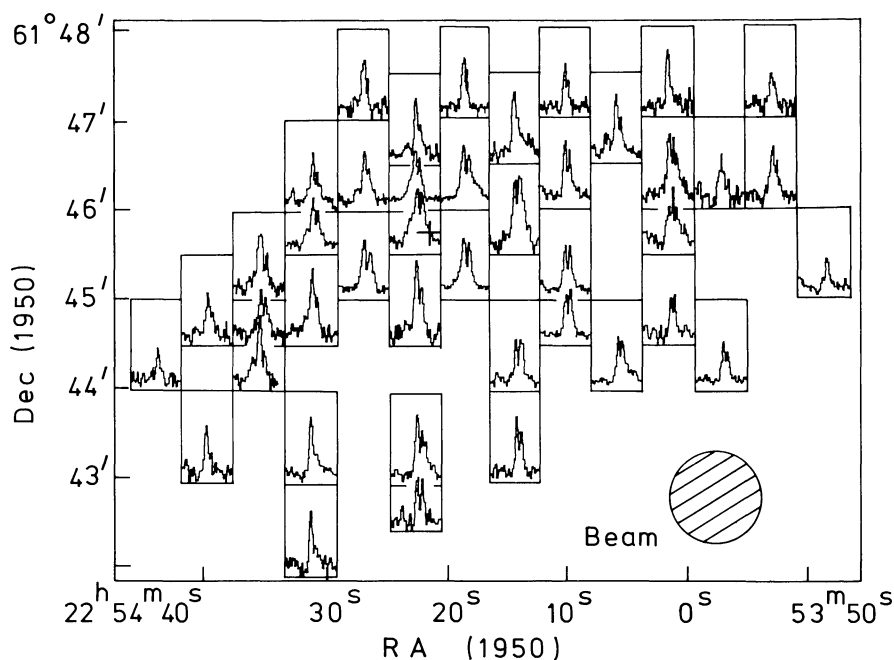


Fig. 1. CO $J = 3 - 2$ spectra of Cepheus A. The extent of each box is from $V_{1, sr} = -42.5$ to $+18.5 \text{ km s}^{-1}$ (horizontal axis) and $T_r^* = -2$ to 14 K . The position of each spectrum is defined by the centre of the box. The cross indicates the reference position used in Figs. 2 and 3

area. About 75% of the spectra also show high velocity wings ($\Delta V_{1K} > 10 \text{ km s}^{-1}$). Although the red and blue wings are obviously not coextensive, we are unable to define a unique axis for a single bipolar flow because of the complexity of the region, which may account also for the disagreement about its orientation between previous studies.

The wing emission is also plotted in Figs. 2 and 3, integrated over various velocity intervals, in order to facilitate comparison with results in other transitions. In Figs. 2a and 2b we show the respective distributions of emission in the blue and red wings,

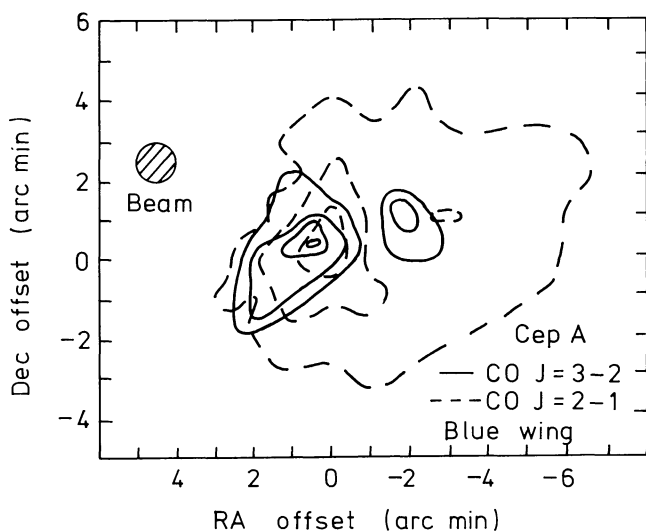


Fig. 2a. Integrated blue wing emission ($V_{1, sr} = -25$ to -15 km s^{-1}) in the CO $J = 3 - 2$ transition. Contour levels 10, 20, 30, 40 K km s^{-1} . Superimposed (broken line) are the 4, 10, 20 K km s^{-1} $J = 2 - 1$ contours for the same velocity interval (Levreault, 1985), for a beamwidth of 1.25 arc min (FWHM). The reference position for Figs. 2 and 3 is RA(1950) $22^{\text{h}}54^{\text{m}}22^{\text{s}}$; DEC(1950) $61^{\circ}45'43''$

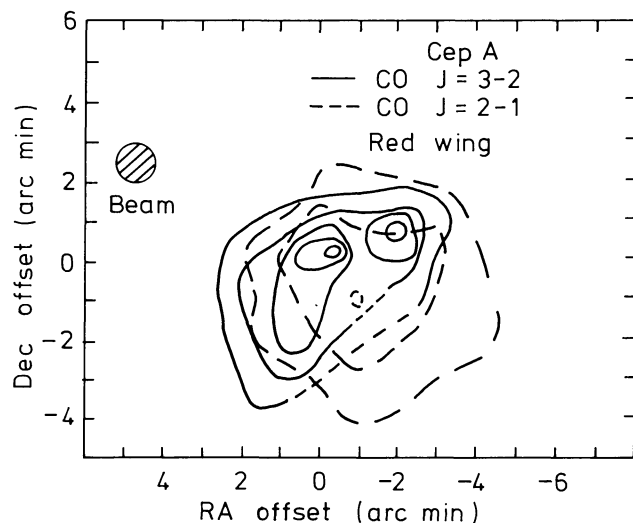


Fig. 2b. Integrated red wing emission ($V_{1, sr} = -5$ to 5 km s^{-1}). CO $J = 3 - 2$ contour levels are 10, 20, 30, 40, 50, 60 K km s^{-1} . Otherwise the same as Fig. 2a

with several contours from the CO $J = 2 - 1$ map by Levreault (1985) superimposed. The velocity intervals are -25 to -15 km s^{-1} (blue wing) and -5 to $+5 \text{ km s}^{-1}$ (red wing).

In our data, the wing emission appears to be distributed around 2 distinct centres, separated by 2 arc min (EW). The more westerly (which we will refer to as Cep A (W)) is situated around the group of HH objects GGD37. A similar spatial structure was seen by Loren et al. (1984) in the integrated wing emission in their $\text{HCO}^+ J = 1 - 0$ spectra, leading them to suggest that two outflows might be present. Our data are consistent with this interpretation. Around the central position of the more easterly source (which we will refer to as Cep A), there is some evidence for an EW bipolarity for the blue and red wings, as seen also in

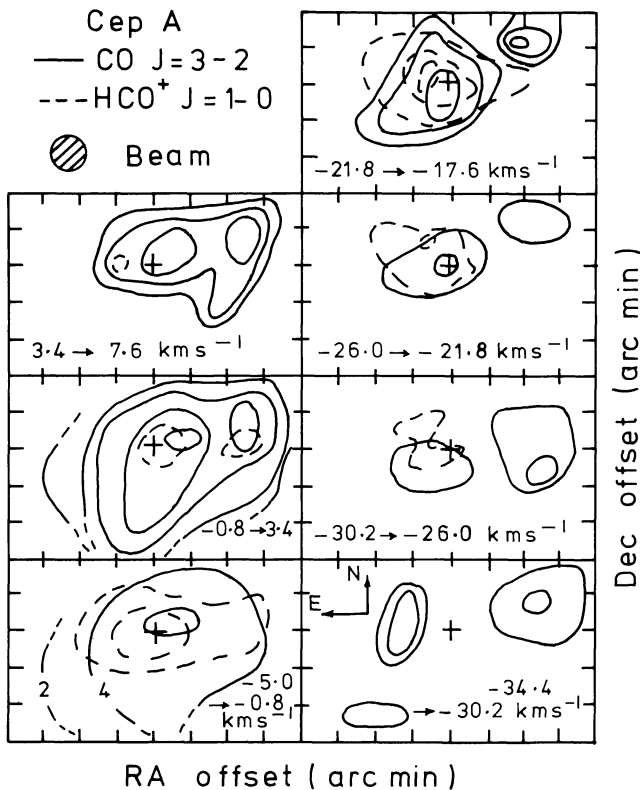


Fig. 3. Comparison of the intensity in the CO $J = 3 - 2$ and HCO⁺ $J = 1 - 0$ lines, for various velocity intervals. The CO contours are for $T_r^* = 0.5, 1, 2, 4, 8$ K (solid lines), averaged over each velocity interval. The HCO⁺ $J = 1 - 0$ contours (Loren et al., 1984) are at $T_r = 0.2, 0.4$ and 0.6 K (broken lines). The beamwidths (FWHM) for the two sets of data are 1 arcmin (CO) and 1.25 arcmin (HCO⁺). See the text for a discussion of comparability between contours

the higher resolution $J = 1 - 0$ data of Hayashi et al. (1985a), although our data would also be consistent with a SE–NW axis. The velocity widths and orientation of the CO data are quite similar to those of the H₂O masers observed over a ~ 0.4 arcsec region by Cohen et al. (1984). For the putative outflow at Cep A (W), though, no significant bipolarity is evident.

Another result from our data is that the $J = 3 - 2$ red wing emission is more extended to the SE of Cep A than either that in the $J = 1 - 0$ line, as shown in the map by Ho et al. (1982) or in the $J = 2 - 1$ transition (Levreault, 1985). This apparent $J = 3 - 2$ enhancement may be due in part to the different beam coupling efficiencies of the telescopes used, and we now attempt a rough estimate of the importance of this. Comparing theoretically derived beam coupling efficiencies η_c (Kutner and Ulich, 1981) for the QMC system on CFHT with those derived for MWO at 230 GHz (e.g. see Levreault, 1985), we find that for a uniform disc source between 1.5 and 4 arcmin in diameter, the ratio $\eta_c(\text{CFHT})/\eta_c(\text{MWO})$ lies between 2.0 and 1.5. Although the Cep A wing emission does not have a uniform disc intensity distribution, inspection of Figs. 2a and 2b suggests that η_c for the wing emission should be equivalent to that of a uniform disc source whose diameter is somewhere between these limits. Therefore, to make a valid comparison between our CO $J = 3 - 2$ data and the CO $J = 2 - 1$ results of Levreault (1985), the CO $J = 3 - 2$ contour levels in Fig. 2 should be divided by a factor between 1.5 and 2. Even after making such a correction, however,

we see from Fig. 2b that, over a considerable fraction of the region, the $J = 3 - 2$ intensity in the red wing is still significantly enhanced over that in the $J = 2 - 1$ transition. The position of peak $J = 3 - 2$ intensity also appears to be situated ~ 1 arcmin to the north of the $J = 2 - 1$ peak. For the blue wing, there is possibly some enhancement, but it is not so pronounced, and the data here are probably consistent with equal intensities in all transitions.

In Fig. 3 we compare the CO $J = 3 - 2$ emission with the HCO⁺ $J = 1 - 0$ data of Loren et al. (1984), which were obtained with the NRAO 11 m antenna. The positions of the peaks in the double structure appear to be the same for both transitions, within the likely errors, but the CO $J = 3 - 2$ emission is strongly enhanced relative to HCO⁺ $J = 1 - 0$. (For example, we estimate that $1 < \eta_c(\text{CFHT})/\eta_c(\text{NRAO}) < 2$ at the relevant frequencies. So for the contours in Fig. 3, the 0.2, 0.4, 0.6 K levels of Loren et al. correspond to $< 0.4, 0.8, 1.2$ K for the purposes of comparison with our data.) Typical enhancement factors are therefore ~ 10 , after correction for beam efficiencies.

4. Discussion

In view of the obvious complexity of the high velocity wing emission, and the difficulties of making an accurate comparison between different data sets, it would be inappropriate here to attempt a detailed quantitative analysis. However, some deductions can be made solely from the qualitative features of our data, together with order-of-magnitude estimates of various parameters. These features may be summarised as follows:

(1) Morphology

The high velocity wing emission has 2 separate peaks, one at the Cep A central position and the other at Cep A (W), near GGD 37. The Cep A high velocity source is bipolar (approximately EW orientation) but the Cep A (W) source, for our spatial resolution, is not.

(2) Intensities

For the red wing, the CO $J = 3 - 2$ emission is significantly enhanced relative to the $J = 2 - 1$ transition. The blue wing data, however, are consistent with equal intensities in all transitions. Also, the CO $J = 3 - 2$ wing emission is more intense by factors $\sim 5 - 10$ than that in the HCO⁺ $J = 1 - 0$ line, after correction for beam effects.

(3) Profiles

In addition to the line broadening already described, most of the line profiles over the wing region are self-reversed.

An enhancement in intensity towards higher transitions is the signature of hot, optically thin and thermalised gas. In the limit of high temperature, low optical depth and high gas density, the predicted line intensities in the CO $J = 1 - 0$, $J = 2 - 1$ and $J = 3 - 2$ transitions would be in the ratios 1:4:9. To give significant enhancements towards higher transitions the following conditions must be satisfied: (a) a gas temperature high enough for all the transitions to fall in the Rayleigh-Jeans regime; (b) low optical depths; and (c) local gas densities which are sufficiently high to collisionally excite the higher transition (s). For the reasons already mentioned, we have not attempted a precise evaluation of the $J = 3 - 2$ enhancement factor $T_r(J = 3 - 2)/T_r(J = 2 - 1)$; we simply use the fact that this factor is significantly greater than

unity and assume that this requires each of conditions (a), (b) and (c) to be at least approximately satisfied.

To satisfy (a), the gas temperature must be sufficiently high that $h\nu/kT$ is < 1 , which for $\nu = 345$ GHz gives $T > 17$ K. This is almost certainly the case for this source because the CO $J = 1 - 0$ peak intensities are of this approximate magnitude (e.g. see Margulis and Lada, 1985) and the dust temperature has been estimated as ~ 40 K (Evans et al., 1981). To deal next with condition (c), we note that, under optically thin conditions, the effect of radiative trapping in exciting the $J = 3 - 2$ transition will be slight, so that local values of the molecular hydrogen density, n_{H_2} , must be high enough to populate the $J = 3$ level of CO by collisions alone. This implies that Cn_{H_2} is $> A_{32}$, where C is the downward collisional rate from level $J = 3$ and A_{32} is the Einstein coefficient for spontaneous deexcitation. Taking $A_{32} = 2.6 \cdot 10^{-6}$ and $C_{32} = 7 \cdot 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ (Flower and Launay 1985), we then have

$$n_{\text{H}_2} > 4 \cdot 10^4 \times (T/40 \text{ K})^{-0.5} \text{ cm}^{-3},$$

the weak temperature dependence occurring because of the proportionality of collisional rates to the average incident colliding particle velocity. For a gas kinetic temperature of 40 K, we find $n_{\text{H}_2} \gtrsim 4 \cdot 10^4 \text{ cm}^{-3}$. This result is self-consistent because, at such densities, the temperature of the gas would be well coupled to that of the dust (Scoville and Solomon, 1974; Goldsmith and Langer, 1978). This density exceeds by an order of magnitude the average value of $6 \cdot 10^3 \text{ cm}^{-3}$ derived by Bally and Lada (1983) from CO observations, but could be reconciled with their result if, for example, there was a significant amount of clumping within the beam.

We next consider condition (b); in particular, we address the question of how likely it is that molecular hydrogen of density $\gtrsim 4 \cdot 10^4 \text{ cm}^{-3}$ will contain optically thin CO. We have run a simple LVG model for levels up to $J = 10$ (for details see e.g. Richardson et al., 1985) in order to estimate optical depths. (For low optical depths, the results are in any case expected to be insensitive to the kinematic model used.) For an assumed kinetic temperature of 40 K and a gas density of $n_{\text{H}_2} = 4 \cdot 10^4 \text{ cm}^{-3}$, we find that an optical depth of unity is obtained for $X_{\text{CO}}/(dV/dR) = 8 \cdot 10^{-8} \text{ km}^{-1} \text{ s pc}$, where X_{CO} is the ratio of CO to $(\text{H}_2 + \text{He})$ abundance and dV/dR is the local velocity gradient. An upper limit to the likely velocity gradient can be obtained by dividing the total velocity width of the line wings (estimated as extending from -25 to $+5 \text{ km s}^{-1}$) by the linear size of the wing emitting region ($\sim 0.6 \text{ pc}$ at an assumed source distance of 730 pc). Hence we estimate an upper limit to the relative CO abundance of $X_{\text{CO}} \lesssim 4 \cdot 10^{-6}$, in contrast to the frequently used value of $X_{\text{CO}} = 8 \cdot 10^{-5}$, which was derived by Dickman (1978) for dark clouds. Despite the many uncertainties in our estimate, most of our assumptions have been somewhat conservative, and this result yields additional plausibility to the indications of previous work that the CO abundance is relatively depleted in this type of region (Wootten et al., 1978; Richardson et al., 1985). A direct consequence of this conclusion is to bring the estimated density above into closer agreement with values calculated from integrated CO $J = 1 - 0$ intensities (e.g. Ho, Moran and Rodrigues, 1982; Bally and Lada, 1983) since that method entails dividing a CO column density by an assumed value for X_{CO} in order to estimate n_{H_2} . A further implication would be that many previous estimates of the masses of molecular outflows may have been serious underestimates. For example, the estimate of $1.6 M_{\odot}$ for the mass of

the redshifted gas (Ho et al., 1982) would now be increased to a lower limit of $32 M_{\odot}$.

How do the above estimates agree with the $\text{HCO}^+ J = 1 - 0$ and $J = 3 - 2$ observations of Loren et al. (1984) towards the wing emitting region? The conclusion from the detection and near similarity of wing intensities in the HCO^+ lines (Loren et al., 1984) was that the outflow contained clumps of density $\sim 1 \cdot 10^6 \text{ cm}^{-3}$. But following similar reasoning about optical depths to those given above, it would seem unlikely that the CO emission from such clumps could have the low optical depths indicated by our observations. Although our density estimate of $= 4 \cdot 10^4 \text{ cm}^{-3}$ was just a lower limit, the more the density is assumed to exceed this value, the more it becomes necessary to deplete the relative CO abundance in order to maintain the condition of optical thinness. On the other hand, simple LVG modelling shows that H_2 densities in the range $1 \cdot 10^4$ to 10^5 cm^{-3} , combined with values of $X_{\text{HCO}^+}/(dV/dR)$ less than $1 \cdot 10^{-8}$, are insufficient to excite the $\text{HCO}^+ J = 1 - 0$ and $J = 3 - 2$ transitions to similar and detectable intensities.

One way of resolving this paradox would be in terms of a 2 phase model of the outflow, in which dense clumps in the flow were surrounded by a less dense interclump medium (e.g. Norman and Silk, 1980; Richardson et al., 1986). In this instance the clumps would be sufficiently dense to give thermalised and optically thick emission in all observed transitions of CO, ^{13}CO and HCO^+ , while their contributions to the absolute observed intensities would be depressed due to beam dilution. The interclump medium would be producing most of the ^{12}CO intensity, but would not contribute much to the HCO^+ emission because of the lower density, nor to the ^{13}CO intensity because of the low optical depth. (A further implication of this model would be that the ^{12}CO and ^{13}CO emission would originate mainly from different phases of the medium, so could not be used in isolation to derive optical depths.) A 2 phase model for the outflow could in addition account for the observation by Loren et al. (1984) that (for telescopes with similar beam characteristics) the $\text{HCO}^+ J = 1 - 0$ intensity in the red wing towards the Cep A central position is lower than that of $\text{HCO}^+ J = 3 - 2$. This is because, under the conditions existing in the interclump medium, any $\text{HCO}^+ J = 1 - 0$ emission from the dense clumps would be heavily absorbed by this less dense material. In contrast, the $\text{HCO}^+ J = 3 - 2$ radiation would not be absorbed because the interclump medium is not dense enough to excite many HCO^+ molecules into the $J = 2$ rotational level.

The foregoing discussion refers to the redshifted wing. The data for the blue wing are consistent with optically thick CO. Ho et al. (1982) presented a model in which a single outflow was situated towards the back face of the cloud, the larger size of the redshifted region being interpreted as due to a relative lack of resistance to this part of the flow as it expanded towards the cloud boundary. This is consistent with our observations also, except that we see 2 flows.

Finally, we consider the self-reversal which occurs in many of the spectra. In Fig. 4, our central CO $J = 3 - 2$ spectrum is shown superimposed on the CO $J = 1 - 0$ and $J = 2 - 1$ (Plambeck et al., 1983) and the $\text{HCO}^+ J = 1 - 0$ (Loren et al., 1984) profiles, in order to compare their self-reversals. All the data are shown with the same channel width of 1 km s^{-1} . (The CO $J = 3 - 2$ spectrum is actually for a position $\sim 15''$ NE of the others but, since the $J = 3 - 2$ reversals in profiles at adjacent points appear to be fairly constant in width and depth, it is

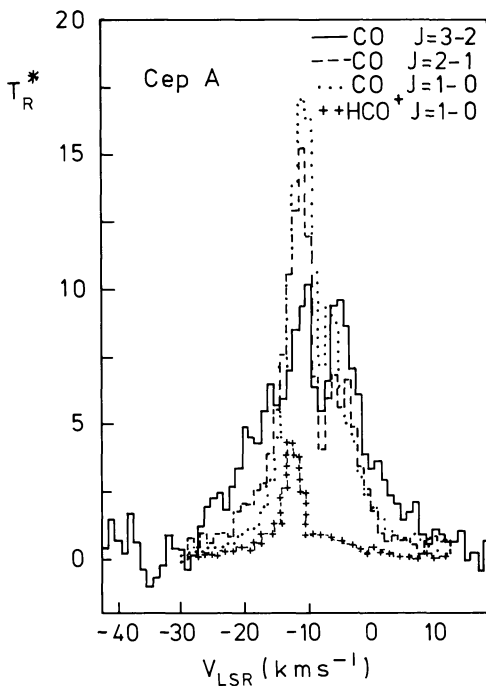


Fig. 4. The CO $J = 3 - 2$ spectrum towards the centre of Cep A, superimposed on the CO $J = 1 - 0$ and $J = 2 - 1$ lines (Plambeck et al., 1983) and the HCO⁺ profile (Loren et al., 1984). All data have been converted to the same velocity resolution of 1 km s^{-1}

unlikely that this slight inconsistency in position will pose any serious problem.) For all the CO transitions, the self-reversal has a width $\sim 1 \text{ km s}^{-1}$, with a possible tendency for the $J = 2 - 1$ and $3 - 2$ features to be broader and deeper than in the $J = 1 - 0$ line. At the spectral resolution of our observations, the velocity of the self-reversal is constant over the region mapped. These characteristics are consistent with absorption of radiation from material associated with the outflow (possibly dense clumps) by less dense and more quiescent gas elsewhere in the cloud. Since typical thermal molecular velocities at 40 K are $\lesssim 1 \text{ km s}^{-1}$, the observed self-reversal widths are probably consistent with thermal linewidths. The spatial extent of the feature is similar to that of the high velocity wings. The absorbing material may therefore also be situated in the core of the cloud, but not be participating in the outflow. As was suggested for the core of DR 21 (Richardson et al., 1986) this could be interclump material within a core region which has already undergone fragmentation. Similar modelling of the self-reversal depths as was carried out for DR 21 indicate densities in the range $n_{\text{H}_2} = 4 \cdot 10^2$ to 10^4 cm^{-3} for the material, as its assumed temperature varies from 500 K to 20 K. However, due to the qualitative similarity of the profiles in the different lines, it is difficult to place meaningful constraints on the kinetic temperature or relative CO abundance.

5. Conclusions

We have mapped an area of $\sim 25 \text{ arc min}^2$ of the Cepheus A outflow, in the $J = 3 - 2$ transition of CO. High velocity wings are present over the region, together with a self-reversal feature at $V_{\text{LSR}} = -8 \text{ km s}^{-1}$ of width $\sim 1 \text{ km s}^{-1}$. The red wing is significantly enhanced in intensity over the lower CO transitions,

implying low optical depths in the redshifted gas. The emission in the blue wing is consistent with equal intensities in all transitions and optical depths > 1 . A comparison of the self-reversals seen in different lines of CO and HCO⁺, together with the relative wing intensities show that the outflow region must be highly inhomogeneous, probably consisting of dense clumps embedded in a less dense interclump medium. According to this model, the interclump medium is responsible for most of the CO wing emission from the outflow and also for the CO self-reversals, which may occur with thermal velocity widths in more quiescent gas in the cloud core.

Acknowledgments. We thank the CFHT for the allocation of telescope time; also the CFHT staff, in particular Bob McLaren, for help in setting up the instrumentation, operation of and assistance at the telescope. We are grateful to SERC for travel grants and funding of millimetre/submillimetre wave astronomy and receiver development at QMC.

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