

The structure and evolution of the dark cloud B 164 under the influence of a bright star, π^1 Cyg

L. Pagani¹, C. Bréart de Boisanger²

¹ DEMIRM, URA 336 du CNRS, Observatoire de Paris, 61 avenue de l'Observatoire, F-75014 Paris, France

² CEA, Centre d'Etudes de Bruyères-le-Châtel, Service PTN, F-91680 Bruyères-le-Châtel, France

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Abstract. We present ^{12}CO , ^{13}CO and C^{18}O ($J: 1 \rightarrow 0$) and ($J: 2 \rightarrow 1$) observations of B 164. This large Bok globule (Bok & Cordwell 1973) is interesting because it is isolated, has a peculiar velocity profile and seems to have been recently compressed on its western side. Assuming that this globule was originally spherical and in rotation, we try to interpret the ^{13}CO and C^{18}O data with a Berne's (1978, 1979) type Monte-Carlo radiative transfer model in which we have introduced rotation. The best solution indicates a large envelope of outwards-decreasing density from 1000 cm^{-3} to 100 cm^{-3} and a relatively small core with central density of the order of 5000 cm^{-3} . CO isotopomers have a very low abundance in this model with the ^{13}CO abundance in the range 10^{-7} – 3×10^{-6} and $\text{C}^{18}\text{O} \approx 1$ – 2×10^{-8} . Next, we show that if π^1 Cyg (Azelfafage, HD 206672), a Be3-III star is at the same distance as B 164 from us, it could be the progenitor of the observed compression. Using a chemico-hydrodynamical (CHD) model (Bréart de Boisanger et al. 1992) we show that the most probable explanation is that the star has just arrived close enough to the cloud to efficiently compress it via the heating of the diffuse interstellar medium and/or the increase in radiation pressure.

Key words: hydrodynamics – ISM: individual objects: B 164 – ISM: kinematics and dynamics – ISM: clouds – stars: π^1 Cyg – radio lines: ISM

1. Introduction

Molecular clouds are often large and complex entities, strongly inhomogeneous and for which we generally have no information on their 3D shape. They are thus difficult to model. One way to eliminate this difficulty is to study isolated objects with a simple apparent geometry such as the small Bok globules. However, since the early radio works of Dickman (1978) and Martin & Barrett (1978), we know that these small globules are usually dense ($3 \times 10^4 \text{ cm}^{-3}$) up to the edge and not very representative

of molecular clouds in general. We have thus become interested in a large Bok globule, B 164 (Bok & Cordwell 1973) as part of our program to study a few inconspicuous Bok Globules (with B157 and L 1014, Robert & Pagani 1993) because its visual aspect, though not round but kidney-shaped, shows a core and a diffuse envelope. To our knowledge, B 164 has never been studied in detail up to now. This cloud is still relatively simple in shape and sufficiently isolated to be a good candidate for radiative transfer models. However this cloud turns out to be more complex than expected with a CO emission map different from the optical shape, a non-linear velocity structure which could be interpreted as rotation and a sharp edge (both visible in CO and on the POSS plate) possibly due to the perturbing action of a nearby star which we have tentatively identified as π^1 Cyg (Azelfafage, HD 206672), a Be3-III star.

If real, the rotation property is interesting because it helps to link the cloud's 3D shape to the velocity field and with a suitable radiative transfer model, we can hope to derive for this cloud relatively accurate and detailed physical parameters. B 164 is also a good candidate for the CHD model of Bréart de Boisanger et al. (1992) with which we can try to track the nature of the perturbing action of π^1 Cyg.

In this paper, we develop the following points: in Sect. 2 we present all the observations, whether ours or collected from previous works and in Sect. 3 we analyze the results of these observations. Section 4 develops the discussion in 4 parts: Sect. 4.1 briefly presents the radiative transfer modeling and results concerning ^{13}CO and C^{18}O and in Sect. 4.2 we derive several important cloud parameters from the combination of the model and of the data. Sect. 4.3 presents the star and its characteristics and finally in Sect. 4.4 we use the CHD code to understand how the cloud can be perturbed by the star. Concluding remarks are given in Sect. 5.

2. Observations

Many observations have been carried out of B 164 (reference position is $21^{\text{h}}44^{\text{m}}53^{\text{s}} + 50^{\circ}52'$, eq. 1950) as summarized below.

Send offprint requests to: L. Pagani

2.1. 3 mm lines

The ^{12}CO , ^{13}CO and C^{18}O ($J: 1 \rightarrow 0$) lines have been observed with POM-1, a 2.5 m telescope at Bordeaux Observatory (Baudry et al. 1981) with a spatial resolution of $4.5'$ and a frequency resolution of 100 kHz (0.26 km s^{-1}). The forward efficiency, η_f , is 95% and the forward scattering and spillover efficiency, η_{fss} , is 90% (Kutner & Ulich 1981). The receiver was equipped with a DSB Schottky diode mixer and calibration was done by chopping against a hot load at ambient temperature. The calibration of POM1 has been checked to be consistent with several other telescopes (SEST, BTL 7 m & CfA 1.2 m). The backend was a 256 channel filter bank of 100 kHz resolution.

Observations were carried out between December 1985 and January 1988. The system temperatures were typically 1300–3000 K for ^{12}CO , 740–1440 for ^{13}CO and C^{18}O . We used frequency-switching by ± 64 channels to perform the observations, with calibrations every 10 minutes. The constancy of the gain was regularly checked by observing the NGC 2264 IR source and S140. The data are presented in the Kutner & Ulich (1981) T_r^* scale.

2.2. 1.3 mm lines

The ^{12}CO , ^{13}CO and C^{18}O ($J: 2 \rightarrow 1$) lines have been observed with POM-2, the twin telescope of POM-1, situated at Plateau de Bure Observatory (Castets et al. 1988). Most of the observations were carried out with the Schottky receiver ($T_{\text{rec}}(\text{DSB}) = 300 \text{ K}$) between December 1988 and May 1989. Its spatial resolution was $2.5'$, the forward efficiency 0.77 and the forward scattering and spillover efficiency 0.6. The frequency resolution was 78 kHz ($\approx 0.1 \text{ km s}^{-1}$).

The system temperatures were between 1300 and 4000 K. Calibration was done by comparing a cold (90 K) and a hot (290 K) load with the sky. In 1992, a SIS receiver was installed with a T_{sys} of 600 to 840 K and a better coupling to the sky ($\eta_f = 0.8 \pm 0.02$ and $\eta_{fss} = 0.68$). We reobserved C^{18}O and a part of ^{13}CO to get better signal/noise ratio. These observations were done in February 1992.

2.3. NH_3 and H I lines

NH_3 (1,1) and (2,2) 1.3 cm and H I 21 cm lines have been observed with the 100 m Effelsberg telescope. NH_3 in August 1986, H I in November 1992. For NH_3 , the spatial resolution is $40''$ and the frequency resolution is 12.2 kHz giving a velocity resolution of 0.15 km s^{-1} . The spectra were converted to main-beam temperature scale by comparison with a reference source, W75 for which we assumed a main beam brightness temperature of 5.4 K (Mauersberger et al. 1985). The 1024-channel autocorrelator backend was split in two parts, one for each line. No signal was detected giving a 3σ upper limit of 0.1 K.

For H I , the spatial resolution is $9.3'$, the sampling was done every $4.5'$ and the frequency resolution is 763 Hz ($= 0.16 \text{ km s}^{-1}$). The calibration was established by comparison

with S7 for which we adopted $T_{\text{MB}} = 99 \text{ K}$ (W. Huchtmeier, private communication). The autocorrelator was again split in two parts with identical velocity resolutions to get the two orthogonal polarizations and the observations were done in an asymmetric frequency-switch mode with a throw of several MHz to avoid emission in the reference part of the spectra.

2.4. Star counts

Preliminary results of automatic star counts using the MAMA machine (Berger et al. 1991) have been used for this study: $10 \times 10 \text{ cm}$ areas of both red ('E') and blue ('O') 1954 POSS glass copies have been digitized and multilevel sampling has been used to detect the stars. The method has not yet been calibrated and some known defects in the data process may underestimate the absolute scale of visual absorption. This scale was obtained with the method described by Cernicharo & Bachiller (1984). The A_v map was compared to the IRAS $100 \mu\text{m}$ map and the similarity between the two was found to be very good.

2.5. Other data

As mentioned above, we collected the IRAS HCON1 survey to produce a map of the $100 \mu\text{m}$ emission around B 164. The 3 other bands (12, 25 and $60 \mu\text{m}$) were too noisy to obtain useful data.

Concerning $\pi^1 \text{ Cyg}$, we have obtained information from J. Zorec (personal communication) and from the Strasbourg CDS SIMBAD data base and we have collected all the available UV data from different satellites: TD1, ANS and SKYLAB, the most interesting one being TD1. The 3 sets of data are completely coherent except at $1350 \text{ \AA}$ where SKYLAB indicates a stronger UV flux than TD1 (-0.4 mag) and we conservatively used only the TD1 data. TD1 UV flux has been dereddened using $E(B-V) = 0.07$ and the mean extinction law given along with the TD1 data.

3. Results

The most important observational results are displayed in Figs. 1–5.

Figure 1 shows the integrated intensity map of ^{12}CO and ^{13}CO ($J: 2 \rightarrow 1$). While the ^{12}CO emission extends further out than the ^{13}CO almost everywhere, the latter is clearly seen to reach the right-hand border at the same place as ^{12}CO with its intensity being maximum close to the edge. The $J: 1 \rightarrow 0$ lines (not shown here) display the same behavior but the edge is smoother due to the coarser spatial resolution. The ^{12}CO outlines a regular, roughly squared shape while the ^{13}CO is more suggestive of an elongated shape tilted at almost 45° and the two isotope peaks do not coincide either.

Figure 2 shows a qualitative picture of the dust absorption from star counts superimposed on the ^{13}CO integrated emission map. The central body of dust has a horseshoe shape with a relatively sharp right-hand border and beyond this edge, the space is remarkably devoid of dust (and of IR emission as indicated by

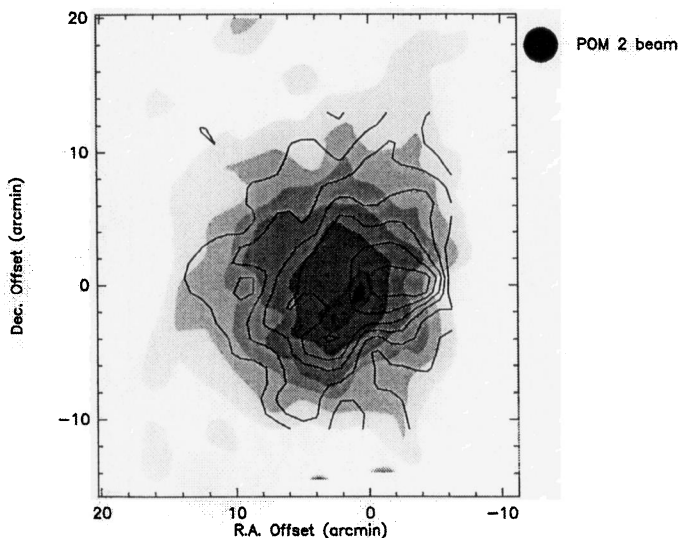


Fig. 1. ^{12}CO and ^{13}CO ($J: 2 \rightarrow 1$) integrated intensity maps of B 164. ^{12}CO greyscale ranges from 1.5 to 7.5 K.km s^{-1} while ^{13}CO contours go from 0.2 to 1.2 K.km s^{-1} by steps of 0.2. Reference position is (eq. 1950): $\alpha = 21^{\text{h}}44^{\text{m}}53^{\text{s}}$ $\delta = +50^{\circ}52'$. Note the ^{13}CO peak position close to the ^{12}CO edge and the coinciding edges on the right-hand side

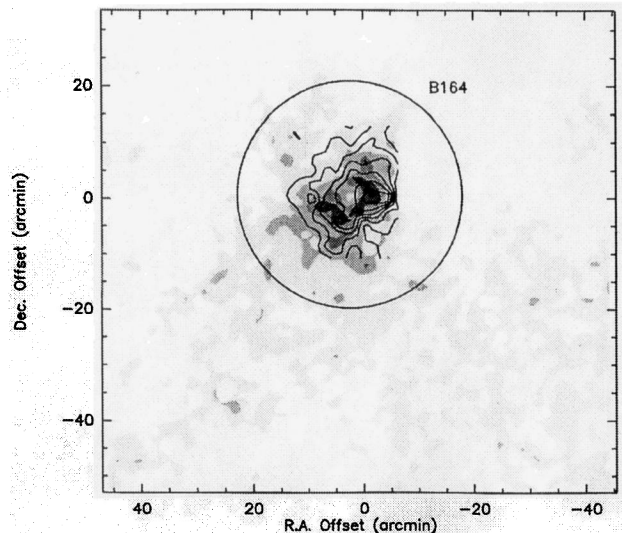


Fig. 2. Dust absorption map (A_v greyscale from 0.15 to 2.5 mag) and ^{13}CO ($J: 2 \rightarrow 1$) contours (same as in Fig. 1). Same reference position as in Fig. 1. Note the sharp limit on the right-hand side of B 164

the 100 μm map not shown here). The sharp edge on the right is also coincident with the edge seen on both ^{12}CO and ^{13}CO maps while dust (and 100 μm emission) expands further away than CO everywhere else.

The ^{13}CO map does not correlate very well with the dust. If the borders of the ^{13}CO cloud follow relatively closely the dust at the 0.3–0.5 A_v level, the dust horse shoe shape is not visible at all in the ^{13}CO map. This is indicative of optically thick ^{13}CO emission. Indeed, Fig. 3 shows that both ^{12}CO and ^{13}CO lines present self-reversed profiles with the absorption dip redshifted with respect to the systemic velocity of the object ($V_{\text{lsr}} = 3.7 \text{ km s}^{-1}$). Such a redshifted absorption line is sometimes interpreted as a sign of gas in contraction. The ^{12}CO and ^{13}CO dips do not occur at the same velocity which means that it is not the same gas which is responsible for both absorptions.

Figure 4 shows 3 position-velocity maps at null declination offset in ^{12}CO ($J: 2 \rightarrow 1$), ^{13}CO ($J: 1 \rightarrow 0$) and ($J: 2 \rightarrow 1$). The peak intensity line from the ^{13}CO ($J: 2 \rightarrow 1$) velocity plot has been overlayed onto the two other maps. It shows that the ^{13}CO ($J: 1 \rightarrow 0$) map is similar in shape though its coarser spatial and velocity resolutions smooth out the details. The ^{12}CO ($J: 2 \rightarrow 1$) strip has some similarities with the ^{13}CO maps. In particular, its two peaks (at $\Delta\alpha = +2'$ and $-1'$ and $V_{\text{lsr}} = 3.2$ and 5 km s^{-1} respectively) lie just ‘outside’ (in the velocity domain) the ^{13}CO peaks. This could be due to the strong self-absorption masking the real peak. The ^{13}CO ($J: 2 \rightarrow 1$) strip which is less affected by optical thickness is the most interesting: this map is clearly asymmetrical with the strongest intensity around $\Delta\alpha = 0$, i.e. close to the western abrupt edge as already noted in Figs. 1 and 2. It is also interesting to note that the signal above 0.6 K delineates a clear velocity shift. The spatial resolution (2.5') and the opacity do not allow us to distinguish between

a chance alignment of two independent fragments along the line of sight and a continuous velocity drift inside the cloud. One possible explanation could be the following: the cloud was originally spherical and in rotation and its western side has been either truncated (e.g. by evaporation or UV destruction) or compressed. In that view, the region around $\Delta\alpha = 0$ would be the dense core rotating in an almost rigid-body fashion and the region beyond $\Delta\alpha \approx +3'$ the trailing envelope. Almost nothing would be left from the original envelope on the western side apart from a possible embryo between $\Delta\alpha = -2'$ and $\Delta\alpha = -5'$ seen in ^{13}CO ($J: 2 \rightarrow 1$) and marginally in ^{13}CO ($J: 1 \rightarrow 0$) on the velocity maps. In the next section, we will try to see if this picture is a reasonable guess of what could be the cloud history and situation.

Figure 5 represents a preliminary attempt to identify a H I halo around B 164. The globule seems to be riding on an elongated H I ridge the peak of which is between 4 and 5 km s^{-1} . The halo seems to be detected through 3 features: an enlargement in velocity width between $\alpha = 0$ and $+20'$ where the cloud stands and similar to the cloud velocity extension, a peak in intensity just behind the cloud between $+20'$ and $+30'$, and very interestingly a ‘tongue’ of H I gas from $10'$ down to $-3'$ between $+4$ and $+5 \text{ km s}^{-1}$ following exactly the ^{12}CO absorption dip all across the ^{12}CO plot. We believe this could perhaps represent the H I halo compressing the ^{12}CO envelope and as far as we know this would be the first time such an interaction is reported. The origin of this compression is discussed further below (Sect. 4.4) and it is suggested that it is due to a backward motion of the molecular cloud against the H I halo.

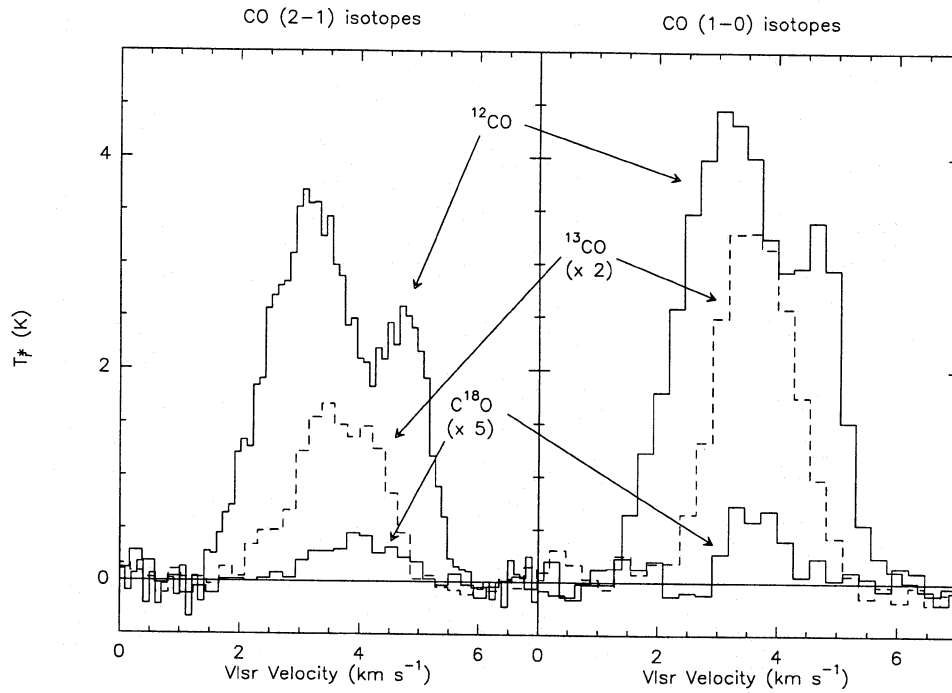


Fig. 3. ^{12}CO , ^{13}CO and C^{18}O ($J: 1 \rightarrow 0$) and ($J: 2 \rightarrow 1$) spectra towards the reference position in B 164. The ($J: 2 \rightarrow 1$) spectra have been degraded to the ($J: 1 \rightarrow 0$) resolution ($4.4''$). The redshifted self-absorption is clearly visible on the ^{12}CO spectra and also on the ^{13}CO ($J: 2 \rightarrow 1$) spectrum though not so deep while the ^{13}CO ($J: 1 \rightarrow 0$) spectrum shows only a flattened peak with a (marginally) lower shoulder at the ($J: 2 \rightarrow 1$) absorption velocity

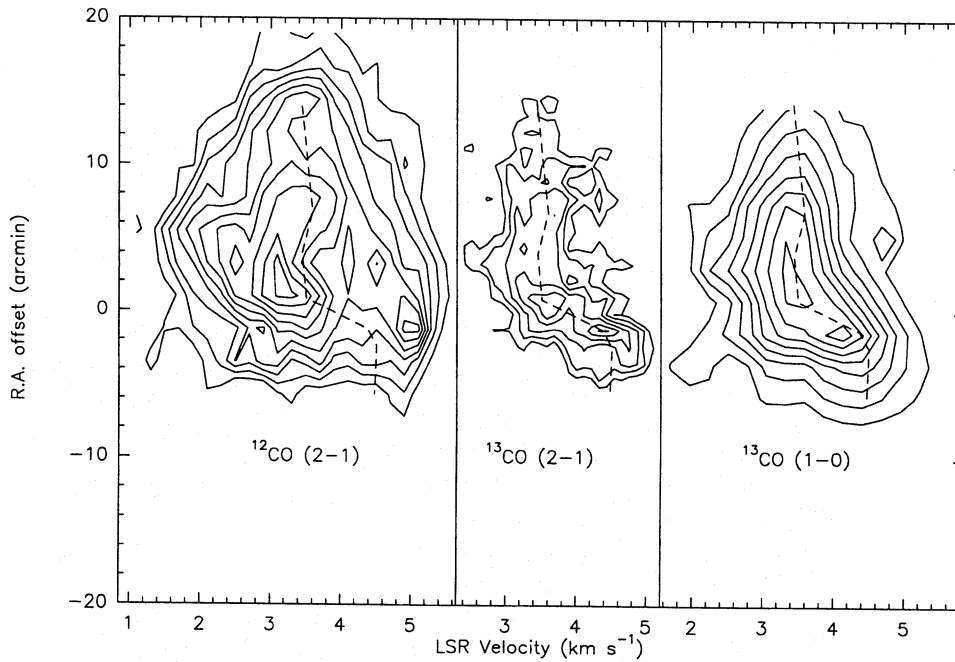


Fig. 4. ^{12}CO ($J: 2 \rightarrow 1$), ^{13}CO ($J: 1 \rightarrow 0$) and ($J: 2 \rightarrow 1$) velocity strip maps taken at null Declination offset. ($J: 2 \rightarrow 1$) data have been Hanning smoothed once. A dashed line traces the peak intensity velocity across the ^{13}CO ($J: 2 \rightarrow 1$) strip. This line has been overlayed on all 3 strips. Levels are from 0.4 to 4 K by steps of 0.4 for ^{12}CO , 0.21 to 0.86 K by steps of 0.13 K for ^{13}CO ($J: 2 \rightarrow 1$) and 0.2 to 1.6 K by steps of 0.2 K for ^{13}CO ($J: 1 \rightarrow 0$)

4. Discussion

4.1. The Monte-Carlo model

Assuming that the cloud was originally spherical and in rotation, we have built a first model to analyse the radiative transfer in it which we briefly present below.

Because ^{12}CO and even ^{13}CO lines are self-reversed here and because of the possible rotation pattern, simple models like LVG are useless because they do not allow gradients of any parameter (except for the necessary radial velocity gradient in the LVG case). Thus we started from an onion-shell model with

spherical symmetry and a Monte-Carlo radiative transfer code (Bernes 1978, 1979) and adapted it to include rotation. We did not consider individual shells as solid rotating bodies but we divided the volume in concentric cylinders to describe the rotation (Fig. 6). Microturbulent, radial and rotational velocities are allowed for and independent descriptions of the core and of the envelope velocity fields can be given. To compare the model with the observations, we compute the emergent intensity along many lines of sight and convolve them with a gaussian pattern to mimic the POM-1 and POM-2 beams. A full map of the cloud can be constructed but we mostly concentrate on the

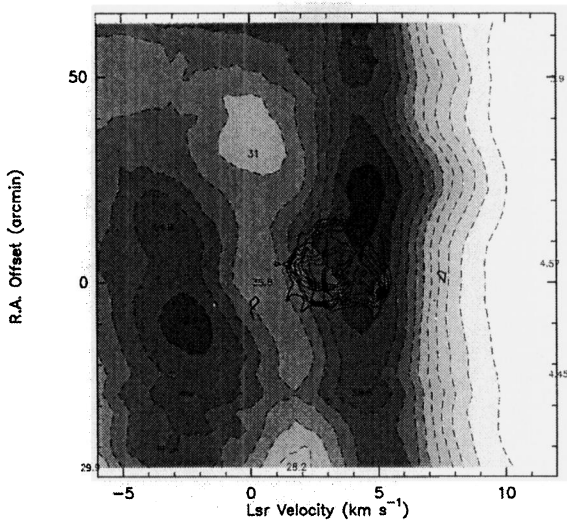


Fig. 5. H I and ^{12}CO ($J: 2 \rightarrow 1$) velocity strip map at null Declination offset. H I beam is $9.3'$ and the sampling is done every $4.5'$. Both sets of data have been Hanning smoothed once. H I levels are from 10 to 60 K by steps of 5 K and ^{12}CO are from 0.4 to 4 K by steps of 0.4. Note the last two H I levels at 55 and 60 K centered on the ^{12}CO absorption dip and the slight deficiency of H I gas on the truncated side of the cloud with respect to its other side

equator i) to produce velocity strip maps directly comparable to Fig. 4 and ii) because the spherical shell structure is not exactly adapted to the structure of the cloud. The latter is true because the core certainly extends over all the height of the cloud even if shrinking somewhat at the extremities while the model presents a round core and thus only at the equator can the model match the cloud. With this model, the different data sets can be fitted independently with their original spatial resolution.

Two solutions are presented here (Fig. 7a,b) which try to fit the ^{13}CO velocity strips of Fig. 4. Table 1 presents the 2 sets of parameters we have used to obtain these results. Three parts can be distinguished: 1) a core of diameter 0.4 pc with medium-density, cold gas, in solid-body rotation, 2) an internal envelope of size 1.92 pc to fit the ^{13}CO extent. Its cold gas is of low-to-moderate density, its rotation is slowing down towards the border and it has a small radial contraction component to match the ^{13}CO dip seen in Fig. 3. Its temperature rises slightly outwards and 3) an outer envelope of external size 2.5 pc, of low density, with little rotational speed and relatively high contraction velocity (0.5 km s^{-1}) to match the ^{12}CO emission only. Its temperature is increasing rapidly outwards to 40 K but its contribution to ^{13}CO emission is negligible. The main difference between the two sets of models is the abundance of ^{13}CO which is about one order of magnitude higher in the former one. Because there are so many possible solutions, we cannot exclude that better solutions may be found with the same model.

The two solutions displayed in Fig. 7 both share common features with the observations but none is completely satisfactory. Solution A (optically thick ^{13}CO) shows the same global shape as the data but is slightly too intense in ($J: 1 \rightarrow 0$) and

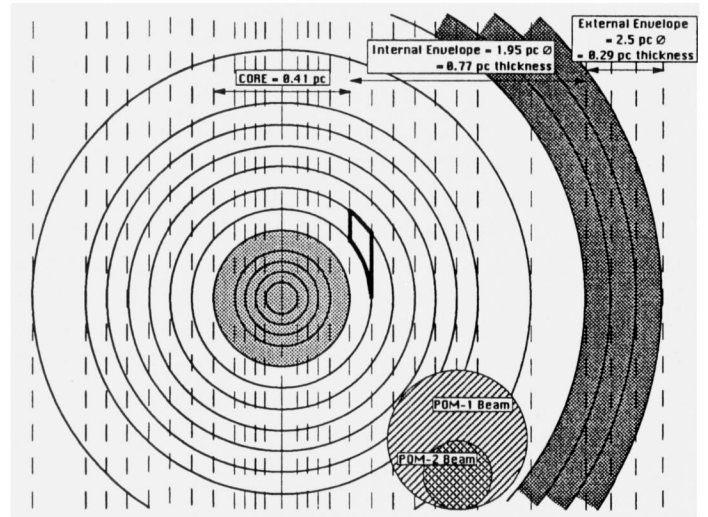


Fig. 6. Monte-Carlo model showing the onion structure of the cloud and the velocity cylinders (dashed lines). Their intersections represent the elemental volumes on which excitation is computed. One of these elemental volumes is delimited by bold lines. The 3 different parts of the cloud are in different shades of grey and the POM-1 and POM-2 beam sizes are shown as well. Note that the core is smaller than the POM-1 beam

the ($J: 2 \rightarrow 1$) spatial extension is too small while solution B (optically thin ^{13}CO) matches the intensity and extent better but the shape is not so close, being centrally peaked and without the small absorption dip. However the two fits are globally satisfactory and confirm that rotation could be a good explanation to the observed velocity strip shapes.

We also have to fit the C^{18}O and ^{12}CO data. C^{18}O is interesting because it is optically thin. In this source however, it is so weak that its observation was problematic, especially at 1.3 mm where we could detect it only in the core and with a rather low signal-to-noise ratio ($0.15 \text{ K [6}\sigma]$ at 2.6 mm and $\approx 0.07 \text{ K [3}\sigma]$ at 1.3 mm for the central position). Its ($J: 2 \rightarrow 1$)/($J: 1 \rightarrow 0$) ratio indicates a mean density of $3\text{--}6 \times 10^3 \text{ cm}^{-3}$, a maximum column density of $\approx 10^{14} \text{ cm}^{-2}$ and its abundance is only $1\text{--}2 \times 10^{-8}$ that of hydrogen. This fractional abundance is a factor of 10 below the usual value found in the literature (see e.g. Crutcher 1985).

From the ^{13}CO model parameters, we tried to reproduce the ^{12}CO observations by simply scaling the ^{13}CO abundance to the ^{12}CO one. This failed and even by varying all parameters we cannot reproduce the observations. More specifically, the ^{12}CO linewidths are too narrow if we use the ^{13}CO microturbulent values (we had to use $V_{\text{rms}} = 1.0 \text{ km s}^{-1}$ instead of 0.6 km s^{-1} for ^{13}CO for the 12 inner layers) and the absorption dip is too wide, displacing the ^{12}CO intensity peaks outwards on the velocity strip maps and making the ($J: 2 \rightarrow 1$) line always too weak (2.8 K maximum instead of $\approx 4 \text{ K}$) and the ($J: 1 \rightarrow 0$) line always too strong (5 to 7 K instead of $\approx 4.5 \text{ K}$) when the ($J: 2 \rightarrow 1$) line was between 2.4 and 2.8 K peak. The correct explanation might be that there exists together with the cold, dense gas a very subthermally excited gas absorbing mostly in

Table 1. Monte-Carlo model parameters for 2 cases. A: optically thick ^{13}CO , growing density in the envelope, B: optically thin ^{13}CO , constant density in the inner envelope. The core, inner envelope and outer envelope are represented by layers 1 to 5, 6 to 13 and 14 to 16 respectively

Layer	Layer radius (pc)	Model A						Model B					
		Rotational velocity (km s $^{-1}$)	Radial velocity (km s $^{-1}$)	Turbulent velocity (km s $^{-1}$)	T_{kin} (K)	$n(\text{H}_2)$ (cm $^{-3}$)	$X(^{13}\text{CO})$ abundance	Rotational velocity (km s $^{-1}$)	Radial velocity (km s $^{-1}$)	Turbulent velocity (km s $^{-1}$)	T_{kin} K	$n(\text{H}_2)$ (cm $^{-3}$)	$X(^{13}\text{CO})$ abundance
1	0.03	0.125	0	0.6	8	5000	4.2E-07	0.225	0	0.7	10	5000	2.4E-07
2	0.07	0.25	0	0.6	8	5000	4.2E-07	0.45	0	0.7	10	5000	2.4E-07
3	0.10	0.375	0	0.6	8	5000	4.2E-07	0.675	0	0.7	10	5000	2.4E-07
4	0.14	0.5	0	0.6	8	5000	4.2E-07	0.9	0.035	0.7	10	5000	2.4E-07
5	0.20	0.8	0.035	0.6	8	5000	4.2E-07	1	0.035	0.7	10	5000	2.4E-07
6	0.27	0.9	0.035	0.6	8	980	1.0E-06	1.1	0.035	0.7	10	1500	3.4E-07
7	0.34	1.0	0.035	0.6	8	880	1.0E-06	1	0.035	0.7	10	1500	3.4E-07
8	0.41	0.9	0.035	0.6	8	780	1.3E-06	0.9	0.035	0.7	10	1500	3.4E-07
9	0.48	0.7	0.035	0.6	8	680	2.0E-06	0.8	0.035	0.7	10	1500	3.4E-07
10	0.55	0.65	0.035	0.6	9	600	2.8E-06	0.7	0.035	0.7	10	1500	3.4E-07
11	0.61	0.625	0.035	0.6	10	520	3.3E-06	0.65	0.035	0.7	10	1500	3.4E-07
12	0.79	0.6	0.1	0.6	11	440	2.5E-06	0.6	0.1	0.7	10	1500	3.4E-07
13	0.96	0.5	0.35	0.6	12	400	8.3E-07	0.5	0.35	0.7	10	1500	3E-07
14	1.07	0.4	0.5	0.6	15	300	4.2E-07	0.4	0.5	0.7	15	150	2E-08
15	1.17	0.4	0.5	0.6	40	200	1.0E-07	0.4	0.5	0.7	40	100	2E-08
16	1.27	0.4	0.5	0.6	40	100	1.7E-08	0.4	0.5	0.7	40	100	2E-08

^{12}CO ($J : 1 \rightarrow 0$) with a larger turbulent velocity. Then, the cloud might be best represented by dense clumps bathing in a diffuse gas. This would suggest that ^{12}CO might be present in the interclump gas (which is also necessary to explain the dip in the ^{12}CO spectrum in Fig. 3 if the medium is clumpy. Note that in that case ^{13}CO should also be present in the interclump gas to explain its absorption dip).

4.2. The cloud distance and properties

To deduce the cloud properties from the model results, we need to know its distance. To our knowledge no distance is known and we think it has a probable distance of 200–250 pc for two reasons: this would match the distance to the π^1 Cyg star (see below) and it would give coherent values between the H_2 column density we deduce from the model and what we roughly estimate for A_v from the star counts. If the cloud were at 400 pc, e.g., the central H_2 column density would be $1\text{--}3 \times 10^{22} \text{ cm}^{-2}$ which would translate to $A_v \approx 10\text{--}30$ mag, obviously much more than what the star counts map suggests. Also the CO isotopomer abundances would be decreased by a factor between 1.6 to 2, putting them even further below their standard values. The distance has thus been set to 240 pc and Table 2 gives all the cloud properties at that distance for both models A and B.

Model A is archetypical of a family of solutions with relatively close features between them. For example, it was not possible to keep $T_{\text{kin}} = 10$ K in the inner layers to obtain both self-absorption and reasonable intensities and we had to go down to 8 K in all cases. Similarly, we had to increase the ^{13}CO absolute abundance in the outskirts of the inner envelope where the density drops and we found out *a posteriori* that the maximum abundance (above 10^{-6}) was reached at A_v in the range 0.5 to

1.5 mag. (from the surface of the cloud). If present chemical models do show a $^{13}\text{CO}/^{12}\text{CO}$ enhancement due to fractionation at $A_v \approx 0.5\text{--}1$ mag (see e.g. van Dishoeck & Black 1988, models T6) they never indicate that the ^{13}CO absolute abundance should peak at low A_v . A good point for this family of solutions is that the ^{13}CO opacity across the center of the cloud is relatively high ($\tau \approx 5$) and is consistent with the fact that dust and ^{13}CO intensity are not correlated on our maps. Within this family, we also have solutions with constant density for each of the three parts of the cloud or with a $1/r$ density law for the envelope. Interestingly, we could not find a good match at all with a $1/r^2$ density law and had to discard such a gradient as possible. One drawback of these solutions is that the maximum A_v is too large by a factor of $\approx 2\text{--}3$ compared to the star counts. This is due to a too large core density which is also possibly contradictory with the absence of NH_3 detection (if this absence is not due to a chemical peculiarity). We have tried to lower the core density, and if the global properties remain the same, the main difficulty is that the maximum ($J : 1 \rightarrow 0$) intensity becomes really too large (greater than 2 K) making the fit a little worse. With a central density of 4000 cm^{-3} the maximum A_v is about 8 and less than 7 if $n(\text{H}_2) = 3000 \text{ cm}^{-3}$.

Model B represents solutions for which the ^{13}CO opacity is low (below 1 typically). This model could work with $T_{\text{kin}} = 10$ K but with relatively high densities ($n(\text{H}_2) = 1500 \text{ cm}^{-3}$ in the inner envelope) and very low CO abundances. Its advantage is a good fit for both ^{13}CO brightness temperatures but of course the ^{13}CO absorption dip cannot be reproduced in this model. Its corresponding total opacity is about 12 mag. which is difficult to reconcile with the dust measurement and there is no ^{13}CO abundance enhancement at $A_v \approx 0.5\text{--}1$.

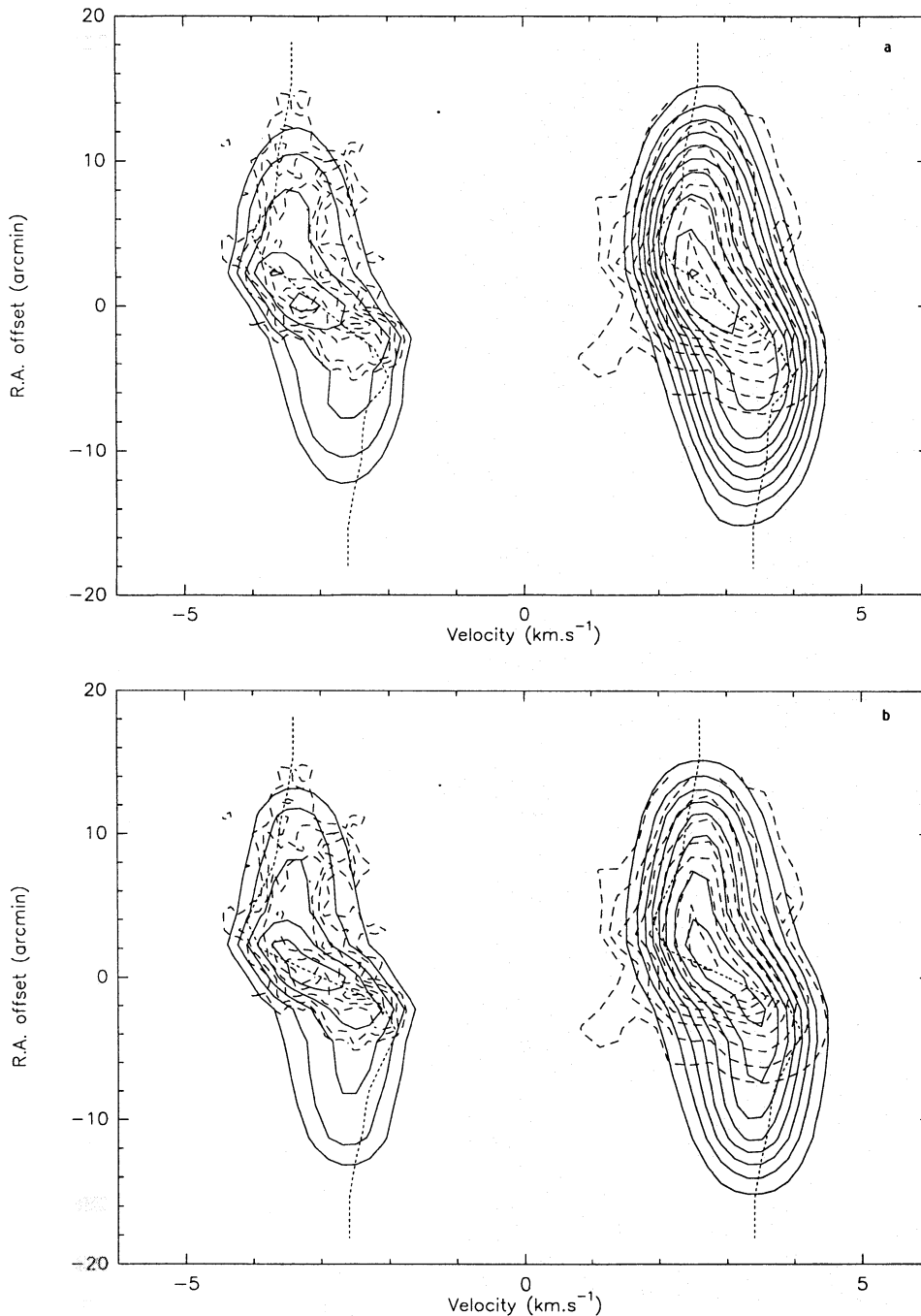


Fig. 7. Two solutions from the Monte-Carlo model are displayed. These solutions represent the null declination offset velocity strip maps for ^{13}CO ($J : 1 \rightarrow 0$) (right) and ($J : 2 \rightarrow 1$) (left). For both solutions we have superimposed the observed data (long dashed lines) and the model rotational velocity (short dashed line). The contour levels are the same for the models and the data and are as in Fig. 4. **a** Optically thick model with decreasing density in the envelope. **b** Optically thin model with constant density in each of the three components

Finally, absolute abundances are interesting to look at. As we mentioned before the C^{18}O abundance is rather low ($1\text{--}2 \times 10^{-8}$), a factor of 10 below the standard value for dark dense cores $X(\text{C}^{18}\text{O}) = 1.6 \times 10^{-7}$ (Myers et al. 1983) and the ^{13}CO abundance itself is not very high: in model A, it reaches a maximum of 3.3×10^{-6} but in the cloud core it is only 4.2×10^{-7} and in model B where it is optically thin, its maximum abundance is only 3.4×10^{-7} ! The $^{13}\text{CO}/\text{C}^{18}\text{O}$ ratio is thus about 25 in solution A and 12 in solution B for the core while in the envelope, we have no C^{18}O ($J : 2 \rightarrow 1$) detection which sets a lower limit on this ratio from > 15 for solution B (where ^{13}CO

is optically thin and is itself underabundant by an order of magnitude) to > 200 for solution A. Thus it appears that this cloud is relatively poor in CO rare isotopes.

We now want to determine the time scale of the perturbation which seems to have truncated or compressed the western side of the cloud. From the model, we now know the rotation curve of the cloud (larger than the apparent rotation curve because of the projection effect: up to 0.5 km s^{-1} here – Fig. 7 and Table 1). What are the time scales involved in the rotation? With a rotation velocity of ≈ 0.7 to 1 km s^{-1} at its surface, it takes 1.3 to 1.8 My for the core to make a turn while the period of the outer envelope

Table 2. Cloud properties for both models. ^{13}CO opacity is given for each layer (columns 2 and 6) and then across the cloud along the line of sight whose impact parameter is the current shell radius. A_v is obtained from the H_2 density per layer, cumulated from the surface (useful for the chemistry) or along the line of sight (as for ^{13}CO) to compare it with ^{13}CO column density and with the visual star counts. The core mass is given for an ellipsoid of same diameter as the model core but of height the total height (the spherical core mass is $5 M_\odot$ for both models A & B). The total mass is given for the original cloud and the missing mass by suppressing the part corresponding to $\Delta\alpha < -6.5'$ that is all the volume beyond 0.5 pc *in projection* from the center (we suppose the cloud cutoff is exactly along the line of sight)

Layer	Model A				Model B			
	$\tau(^{13}\text{CO})$	$\tau(^{13}\text{CO})^a$	A_v^b (mag)	A_v^a (mag)	$\tau(^{13}\text{CO})$	$\tau(^{13}\text{CO})^a$	A_v^b (mag)	A_v^a (mag)
1	0.13	5.13	4.20	9.38	0.02	1.03	5.55	12.05
2	0.14	5.10	3.68	9.14	0.0228	1.03	5.03	11.73
3	0.14	4.99	3.15	8.72	0.0229	1.02	4.50	11.11
4	0.14	4.62	2.63	8.06	0.0238	1.01	3.98	9.12
5	0.16	4.65	1.58	4.15	0.0473	0.94	3.66	9.01
6	0.13	4.45	1.37	3.87	0.0343	0.92	3.35	8.86
7	0.12	4.39	1.19	3.57	0.035	0.89	3.03	8.65
8	0.12	4.36	1.02	3.26	0.0338	0.87	2.72	8.39
9	0.19	4.70	0.88	2.97	0.0341	0.83	2.40	8.08
10	0.26	4.66	0.75	2.68	0.0349	0.79	2.09	7.70
11	0.27	3.33	0.65	2.42	0.0358	0.71	1.77	7.24
12	0.50	0.94	0.41	1.94	0.0811	0.55	0.96	5.58
13	0.13	0.28	0.18	1.17	0.0877	0.01	0.11	0.64
14	2.81E-02	0.05	0.09	0.70	5.82E-04	0.01	0.06	0.42
15	4.96E-03	0.00	0.03	0.30	4.19E-04	0.00	0.03	0.30
16	4.69E-04	0.00	0	0.00	4.09E-04	0.00	0	0.00
	Total volume (cm^{-3})		Total mass ($M_\odot$)	Core mass ($M_\odot$)	Missing volume (cm^{-3})	Missing mass ($M_\odot$)	Max. ^{13}CO opacity	Max A_v
Model A	2.48E+56		140	31	5.45E+55	23	5.1	9.5
Model B	2.48E+56		310	31	5.45E+55	49	1.04	12.2

^a Along the line of sight.

^b Cumulated from the surface.

Table 3. π^1 Cyg parameters

Names: Azelfafage, 80 Cyg, HD 206672, HR 8301, SAO 33665, BD +50 3410, etc.	M : $6.9 M_\odot$ $\log g$: 3.6
Pos. Eq. (1950): $21^{\text{h}}40^{\text{m}}19^{\text{s}} + 50^\circ57'39.1''$	$E(B-V)$: 0.07 mag
Proper motion ^a : $+0.001''$ (3), $+0.001''$ (3)	V : 4.67 mag
Spectral type: Be 3–4 III	d^b : $240 \times e^{0.461 \text{ dV}}$ pc
M_v : -2.45 mag (Photosphere only)	Distance to the cloud center: $43' 30''$
M_{bol} : -4.17 mag (Photosphere only)	At 240 pc it gives a distance of: 3 pc
T_{eff} : 17170 K (Photosphere only)	Estimated UV flux at 1000 Å and at 3 pc
L : $3800 L_\odot$ (Photosphere only)	distance: $2.8\text{--}3.8 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$
R : $6.93 R_\odot$	

^a From the PPM catalogue, (R.A. and Dec. variations in mas yr^{-1}), precision is given for the last digit.

^b dV is the emission excess in the V band due to the circumstellar envelope (dV is probably between -0.3 and -0.1 for this type of star).

is 20 My. If we consider that the perturbation has been recent enough so that the perturbed gas has not yet reached the other side of the cloud, we can say that the perturbation is younger than approximately half a rotation period. That is 10 My for the ^{12}CO envelope and less than 1 My for the core edge (but the core was forcibly reached later than the envelope by the perturbation).

If we suppose that the cloud's eastern side is still unperturbed and the rotation axis is at its original position, we can estimate the original size of the cloud (i.e. the size before the perturbation began) by symmetry and thus 'reconstruct' the missing western side. We also need to make the hypothesis that the cut-off is seen 'edge-on', a likely situation given the aspect of the maps and has not had much time to rotate. In that case, we find that a

segment of height ≈ 0.75 pc is missing, representing a volume of $\approx 5.5 \times 10^{55} \text{ cm}^3$ or $\approx 2 \text{ pc}^3$ which represents about 20% of the total spherical volume. In terms of mass, the loss (or the displacement if the gas has been compressed) is only 12 to 15% of the total mass (see Table 2) as the envelope is less dense than the core.

What is the source of the perturbation? How can a few tens of solar masses be destroyed, evaporated or compressed? π^1 Cyg, an early type star seems to be the best candidate to explain what happened. We now present its characteristics and analyse its action.

4.3. π^1 Cyg

π^1 Cyg is listed in many catalogues (see Table 3). It is a bright blue star of type Be 3–4 III. Its actual distance depends on the V excess correction due to the circumstellar envelope which reprocess a part of the UV shortwave light. For this type of star, the excess can be usually between 0.1 and 0.3 indicative of a distance of 200 to 240 pc in our case.

From the tables of Maeder (1988) the age of the star is 41 Myr, that is 4 times more than the upper limit on the perturbation outset. This would mean that the star has been moving and has just arrived at its present position. Indeed, though very weak and uncertain, a proper motion is indicated for this star of a few milliarcseconds per year in the direction of the cloud (PPM catalog). This motion is to be considered cautiously but is nevertheless large enough to solve the time discrepancy. At a distance of 240 pc, a projected velocity of 1 km s^{-1} ($= 1 \text{ pc Myr}^{-1}$) on the sky plane corresponds to 1 milliarcsecond year $^{-1}$. The star can only act on the cloud when it is close enough (within a few pc), that is in the last few Myr in agreement with the time limit indicated above.

A rapid estimate shows that the star emits enough far-UV photons in a few My to destroy all H_2 molecules but how can the dust be swept away? To go further in the analysis, we need to use a model including hydrodynamics and out-of-equilibrium chemistry of hydrogen which we will present in the last subsection (4.4). To run this model we also need to know what is the UV flux added by the star to the UV interstellar radiation field (ISRF) as given by Draine (1978) e.g. In the absence of data below 1400 Å, we have tried to compare the TD1 UV data to Kurucz (1979) star models to extrapolate the flux at 1000 Å though these models are only intended to represent the star photosphere. As expected the flux is weaker than predicted because of photon reprocessing in the envelope. Its departure increases with decreasing wavelength ranging from 0.66 times the Kurucz value at 2,500 Å to 0.48 at 1400 Å. If we suppose this trend to be constant, we can grossly estimate the UV flux at 1000 Å and find that 3 pc from the star, the total (star + ISRF) UV flux could be a little more than twice the standard UV flux (Draine 1978).

4.4. Hydrodynamical simulations

In order to estimate the possible influence of this star, we have calculated the dynamical and chemical evolution of a molecular

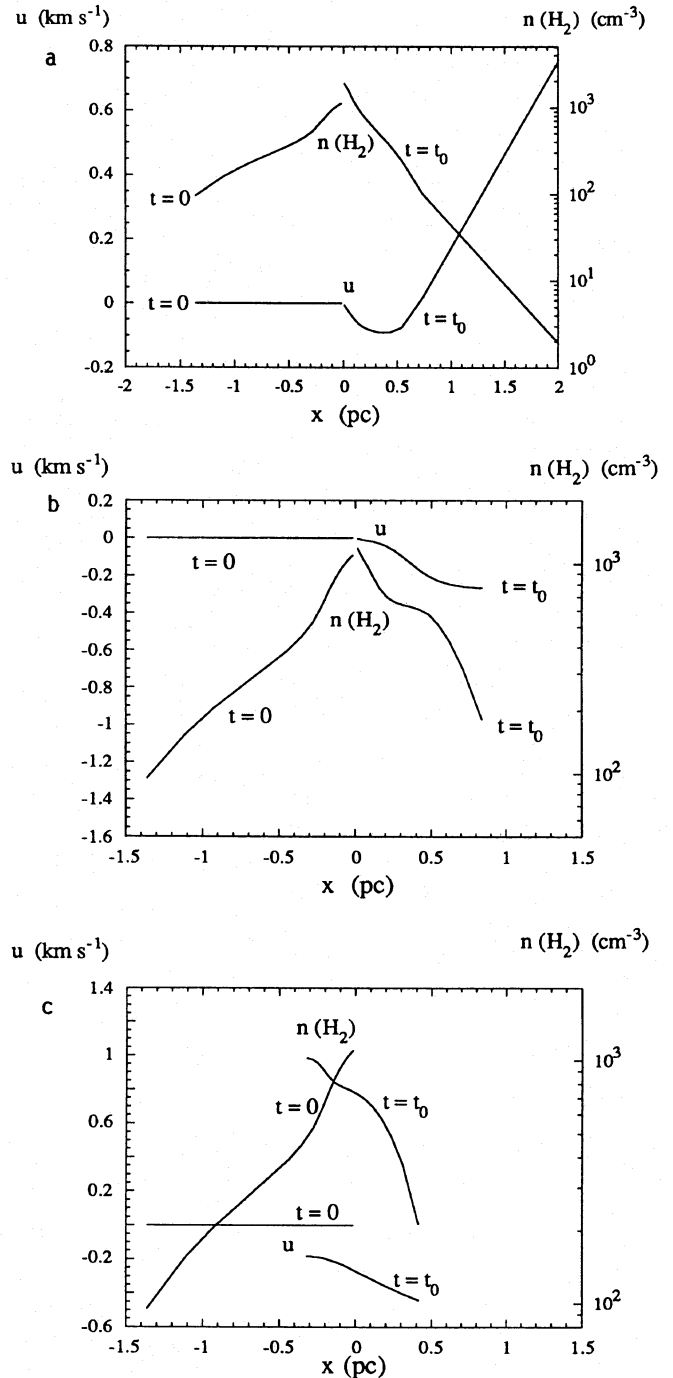


Fig. 8. Velocity and H_2 density profiles of the two sides of the cloud (left: unperturbed and also mirrored initial conditions for the perturbed right side). The positive velocities correspond to gas expansion, and the negative ones to compression. **a** in the case where the external surface is maintained at a constant pressure $P = P_0$ and the central interface is fixed. **b** the external surface is maintained at a constant pressure $P_{\text{ext}} = 2 P_0$; the central interface is still fixed. **c** an inward acceleration is imposed to the external surface and the central interface is maintained at a constant pressure, equal to the initial one P_0

cloud exposed to a varying UV interstellar radiation field, in a manner similar to that presented, in the frame of 2D hydrodynamical simulations, in Bréart de Boisanger et al. (1992).

It is difficult to determine precisely the overall effect of a moving star on its environment and particularly on the chemical, thermal and dynamical state of a neighbouring cloud, since it does include many processes: for example, if the star is approaching, the enhancement of the UV field intensity at the surface of the cloud will result mainly in gas heating – through photoelectric effect on dust grains and photoionization of C I and PAH – and dissociation of molecules – especially H_2 and CO. But, it also will certainly entail the heating of the diffuse intercloud medium and an increase in the radiation pressure exerted on dust grains, which could be transferred to the gas by drag forces, if gas and grains are strongly coupled. This last effect can be roughly estimated in the present case: from the expression given by Franco (1991) for the radiation pressure, it appears that at the cloud edge and for a UV field intensity equal to twice the standard one, it is comparable to the thermal pressure; moreover, the braking time for grains at the edge of the cloud is short ($t_s = 10^{-2}$ Myr, Spitzer 1978): the coupling between gas and grains is then certainly strong, so that the drag force could result in cloud compression and backward motion.

In any case, it is beyond the scope of this simple study to describe in detail the interaction between radiation pressure, dust grains and gas, and the evolution of the diffuse intercloud medium. As a first step, we restricted ourselves to adopt different prescriptions for the conditions imposed at the edge of the cloud which faces the star. Moreover, since we do not know whether the star is approaching the cloud or moving away from it, the two situations have been examined. Furthermore, the cloud rotation has not been taken into account and magnetic field has been neglected for simplicity and because of the lack of observations concerning its strength and direction.

4.4.1. Cloud model

We have used a simplified version of a 1D chemico-hydrodynamical model, in which the time-dependent hydrogen chemistry (H II , H I , H_2) is followed with a small chemical network. Self-shielding of H_2 is treated using the escape probability formalism described by de Jong (1980). The abundances of the other species – essentially C II, C I and CO which govern the thermal balance – are calculated assuming chemical equilibrium, for the instantaneous local density, temperature and UV field intensity. Realistic cold interstellar gas heating and cooling processes have been taken into account (de Boisanger & Chièze 1991). The kinetic chemical equations, coupled to the hydrodynamical ones, are solved in each zone of the cloud model and at each time step, using an implicit scheme.

Initially, the star is supposed to be sufficiently far from the cloud so that its contribution to the total UV flux at the cloud surface is negligible: the cloud is then only exposed to the standard background UV field. The unperturbed cloud model has a half-length of 1.5 pc. The initial density and temperature are calculated at thermal, chemical and isobaric equilibrium (grav-

ity has not been taken into account in this study): from the outer edge to the center, they vary from $n_{\text{H}} = 250 \text{ cm}^{-3}$ and $T = 55 \text{ K}$ to $n_{\text{H}} = 2200 \text{ cm}^{-3}$ and $T = 8 \text{ K}$ (these values are close to those of model A seen above); the total internal visual extinction of this half-cloud model is $A_v = 2 \text{ mag}$. The cloud surface is assumed to be in pressure equilibrium with the diffuse intercloud medium at a pressure $P_0/k = 10^4 \text{ K cm}^{-3}$.

As said before, the simulations begin at a time for which the star is far from the cloud. As time evolves, the star approaches the cloud, and we define t_0 as the moment at which it is at a distance of 3 pc from the cloud. If the impact parameter is less than 3 pc, the star continues to come closer, until the minimum distance is attained, and then begins to move away: it is found once again at a distance of 3 pc from the cloud, at a time that we call t_1 .

4.4.2. Results

The different simulations we have made show that the observations are more easily explained in the case where the star is approaching the cloud (that is if the present time corresponds to $t = t_0$). Indeed, when the star goes away, the cloud inertia complicates its evolution and at time $t = t_1$, the density and velocity profiles are very different from the observations, whatever the starting conditions are.

The results presented here in Fig. 8a–c correspond to simulations in which the star velocity and the impact parameter have typical values, $v_{\text{star}} = 1 \text{ km s}^{-1}$ and Impact Parameter = 1 pc. The density and velocity profiles are those obtained when the distance between the approaching star and the cloud corresponds to 3 pc ($t = t_0$) in three characteristic cases. The edge of the cloud is then exposed to a UV field of intensity equal to slightly more than twice the standard one.

(1) In the first case (Fig. 8a), we did not consider the radiation pressure and the heating of the diffuse intercloud gas, so that the external surface is maintained at a constant pressure equal to the initial one. The central interface is fixed. As the star comes closer, the gas temperature and pressure in the outer layers of the cloud increase due to enhanced heating: the cloud expands with velocity $v < 0.8 \text{ km s}^{-1}$. At the same time, a fraction of the H_2 molecules is photodissociated, but only near the surface. The H_2 density profile is smooth and a large H I halo develops in front of the cloud, contrary to what is possibly suggested by the observations (Fig. 5).

(2) In the second case, the likely effect of radiation pressure and of diffuse intercloud gas heating is examined. To mimic these two effects we have increased the pressure P_{ext} imposed at the external surface. The central interface is still fixed. If P_{ext} is greater than or equal to $2 P_0$, the cloud heating is not sufficient to counterbalance the outer pressure so that it does not expand as in the preceding case but rather contracts slowly when the star comes closer. The density profile is then sharper in front of the star than on the opposite unperturbed edge as can be seen on Fig. 8b which corresponds to $P_{\text{ext}} = 2 P_0$. This case seems in better agreement with the observations than the first one, but an even more realistic model can be proposed.

(3) The third case corresponds to a “pushed” external surface and a free central interface. The effect of the radiation pressure is now mimicked by imposing an acceleration to the external surface: it is then moving inwards with a velocity which increases as the star approaches, is maximum and equal to $v_{\text{surface}} = -0.5 \text{ km s}^{-1}$ when the distance between the star and the cloud is minimum (that is 1 pc) and diminishes as the star goes away. The central interface is maintained at a constant pressure equal to the initial one: this condition allows us to estimate the recoil of the perturbed part into the unperturbed one, due to the compression.

At $t = t_0$, the face of the cloud exposed to the enhanced UV flux exhibits a sharp edge and its surface is at 0.4 pc from the center, comparable to what is observed (Fig. 8c): indeed, although the heating rate increases in the cloud as the star approaches, the pressure exerted by the outer surface, becomes stronger and stronger and remains always dominant, so that this part of the cloud condenses and recoils with velocity $v = -0.4 \text{ km s}^{-1}$. Due to the increase in the radiation field a fraction of molecular hydrogen is photodissociated as in the preceding case, but since the density is getting higher, the H_2 formation time scale diminishes and the fraction of H I remains small. The whole cloud appears clearly asymmetric: as observed (Fig. 5) there is a lack of gas between the cloud and the star because the original cloud envelope has been swept up and compressed. Since gas and dust are surely strongly coupled, this could explain why there is so little dust in front of the cloud on the star side (Fig. 2).

4.4.3. Is the cloud moving backwards?

In spite of numerous approximations the last dynamical model discussed above reproduces well the general characteristics – as derived from the observations – of the part of the cloud B 164 which faces π^1 Cyg. It is then conceivable to think that the star motion is responsible for the cloud shape and dynamics.

Moreover, the strong receding of the perturbed part of the cloud, as shown in the last case, can let one think that in fact, all the cloud is moving backwards under the action of the star. This could explain why the ^{12}CO envelope seems to shrink: this diffuse envelope is being pushed against the H I halo which somewhat resists. As mentioned above, this would explain why the peak H I emission corresponds to the redshifted absorption dip of the ^{12}CO envelope in Fig. 5.

5. Conclusion

B 164 is a large Bok Globule with interesting features. We have shown that if both the rotation hypothesis and the distance estimate are correct, we can deduce the physical conditions and trace recent evolution of this cloud during the last few Myr under the influence of the star π^1 Cyg. It provides a good opportunity to test several types of models: radiative transfer, chemical and dynamical models. It shows that even quiescent, unspectacular clouds are not inert masses of gas and can bring interesting information on the life of the interstellar medium.

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