J. Astrophys. Astr. (1994) **15**, 157–163

Observations of the Bright-rimmed Molecular Clouds near the Cepheus OB2 Association

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Received 1994 March 31; accepted 1994 April 18

Abstract. Massive stars have significant influence on the evolution of the interstellar medium. Bright rims, cometary morphology of clouds, as well as their motion are some examples of the influence of massive stars on nearby molecular clouds. The cometary clouds in the Gum-Vela region are very good examples. In an attempt to understand the kinematics of the clouds in such regions we have carried out CO line observations towards bright-rimmed clouds near the OB Association Cep OB2. The radial velocities of the clouds are consistent with an expansion of the system at $\approx 4\,\mathrm{km s^{-1}}$ away from the dominant O6.5 V star in the association, HD206267. We find the rocket mechanism to be the most likely cause for expansion as found for both the Gum-Vela and the Rosette globules. We conclude that such expanding motions are quite common in regions near massive stars and make a brief comparison of the Cepheus system with the Gum-Vela system.

Key words: Bright-rimmed clouds—OB associations.

1. Introduction

Bright-rimmed clouds are typically found in the vicinity of massive stars. They are seen as patches of obscuration with bright rims on the side facing the stars and sometimes a tail like extension on the other side. Their peculiar morphology is believed to be caused by the effects of UV radiation and stellar winds from young stars. Some of these clouds show evidence for on-going low mass star formation. Sizeable populations of such clouds exist in the Gum-Vela region (Zealey *et al.* 1983; Reipurth 1983), the Rosette Nebula (Block 1990, 1992; see also Schneps, Ho & Barret 1980), the Cep OB2 region (containing IC 1396) (Gyulbudagyan 1985), and the Orion region (Bally *et al.* 1991). Catalogs of bright rimmed clouds have been compiled by Sugitani, Fukui & Ogura (1991) and Gyulbudagyan (1985). Studies of the clouds in the Gum-Vela region have shown that they are expanding at $\approx 12\,\mathrm{km s^{-1}}$ about a common central region containing massive stars (Sridharan 1992). Motion away from the central stars has also been seen in the Rosette globules at $\approx 6\,\mathrm{km s^{-1}}$ (Patel, Xie & Goldsmith 1993). In both these cases the *rocket effect* arising from the anisotropic illumination of the clouds appears to be the mechanism accelerating the clouds away from the stars. These observations are in agreement with the theory of Bertoldi and McKee (1990) for such clouds. In order to find out if such motions are prevalent in other regions with massive stars, and to develop, an evolutionary scenario for comparison with theory, it is necessary to study many regions near OB associations. As a step in this direction we studied the bright-rimmed clouds near the OB association Cep OB2.

The Cep OB2 association is at a distance of 750 pc, with the dominant member being the O6.5 V star HD206267 (SAO36266) which excites the HII region IC 1396. This region is rich in bright-rimmed clouds (globules) which are distributed over an area of diameter 3°. The lack of well developed tail like extensions possibly indicates an earlier stage of evolution compared to the Gum-Vela region. Gyulbudagyan (1985) has identified and classified the globules here into four radial systems based on their orientation and morphology. The clouds with bright rims (category *a*) all have their rims perpendicular to the line joining them to the star HD206267 with extensions pointing away from it. From CO observations of these clouds it was found that clouds classified into different groups also had different radial velocity ranges (Gyulbudagyan, Rodriguez & Canto 1986). The clouds in this region were also observed by Heske & Wendker (1985) in H_2CO absorption. Based on a coarse survey of the molecular clouds in this region, Leisawitz, Bash & Thaddeus (1989) suggested that these clouds may be receding from the central star. Evidence for on-going star formation in these clouds has been found from IRAS data and from the presence of bipolar outflows (Sugitani *et al.* 1989; Sugitani, Fukui & Ogura 1991; Schwartz, Gyulbudagyan & Wilking 1991; Duvert *et al.* 1990).

In this paper we report additional CO observations and a new analysis of the radial velocities of the clouds using data both from our own observations and the previous studies. The next section describes the observations. In section 3 we analyse the radial velocities of the clouds and show that the system is expanding. Section 4 deals with the possible causes for this expansion.

2. Observations

We observed 21 clouds in the $J=1\rightarrow 0$ transition of CO at 115.271 GHz using the 10.4 m millimeter-wave radio telescope at the Raman Research Institute during 1993. Their co-ordinates were obtained from the POSS plates. An acousto-optic spectrometer with a resolution of 100 kHz and coverage of 30 MHz was used giving a velocity resolution of 0.26 $\mathrm{km s^{-1}}$. An ambient temperature chopper was used for calibration. All the observations were done in the frequency switched mode. Line center velocities were obtained by fitting gaussians to the lines. Table 1 lists the positions observed along with the parameters of the detected lines. Observations of a few locations behind the bright rims show similar velocities. Using repeated observations of one of the clouds we estimate the error on the velocities obtained to be 0.05 $\mathrm{km s^{-1}}$.

3. Analysis of the radial velocities

A comparison of our velocities with those of Gyulbudagyan, Rodriguez & Canto (1986) and Heske and Wendker (1985) shows good agreement. Cloud 11 shows two components, as was also found by Gyulbudagyan, Rodriguez & Canto (1986). This is interpreted as due to material belonging to different categories of globules (of Gyulbudagyan 1985) falling along the same line of sight. We assume a distance of

Table 1. Summary of observations.

No.	Co-ordinates (1950.0) ra h	m	s	dec °	′	″	T_a^* K	v_{LSR} kms^{-1}	v_{fwhm} kms^{-1}	T_{rms} K
1	21	34	11	57	12	36	1.67	−8.9	2.1	0.30
2	21	38	44	57	42	12	2.97	−0.7	1.3	0.32
3	21	36	53	57	44	10	4.27	0.1	1.6	0.39
4	21	36	19	57	34	22	2.29	0.3	2.3	0.27
5	21	39	1	58	2	42	2.13	0.4	3.2	0.27
6	21	31	29	57	43	54	1.41	−6.6	1.1	0.25
7	21	34	25	58	22	43	1.46	−3.7	0.9	0.28
8	21	31	14	57	38	13	2.90	−4.3	1.6	0.25
9	21	31	46	57	17	21	4.79	−5.6	1.6	0.28
10	21	44	46	57	9	25	4.50	−2.4	2.1	0.12
11	21	38	52	56	21	54	1.73	1.1	1.6	0.16
							1.39	6.6	1.0	0.16
12	21	31	41	57	16	12	4.62	−5.8	1.4	0.36
13	21	32	2	57	50	5	3.73	−5.3	1.7	0.24
14	21	34	35	58	18	9	4.42	−4.0	1.8	0.24
15	21	34	40	57	14	3	6.32	−8.4	2.2	0.24
16	21	38	53	56	22	16	1.38	0.7	2.8	0.27
17	21	39	10	58	2	28	2.25	1.0	5.9	0.23
18	21	44	30	57	12	28	2.90	−2.0	1.9	0.17
19	21	44	38	56	55	4	7.10	−2.4	2.3	0.36
20	21	44	52	57	4	44	3.30	−2.2	2.9	0.25
21	21	45	0	56	58	28	3.91	−2.3	2.0	0.19

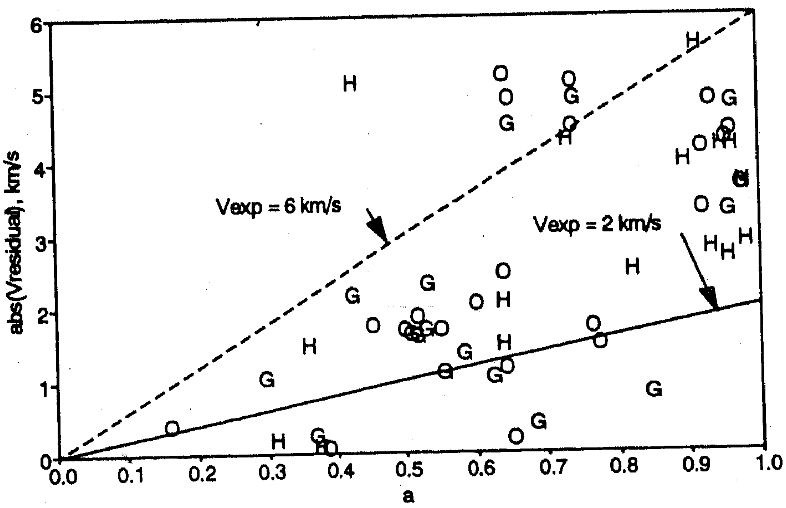

Figure 1. Absolute value of the residual velocities plotted against $(1-\sin^2\theta/\sin^2\theta_{max})^{1/2}(\equiv a)$. The symbols G, H and O indicate data from Gyulbudagyan, Rodriguez & Canto (1986), Heske & Wendker (1985) and our measurements respectively. The straight lines shown represent shells expanding uniformly at 2 and 6 kms^{-1}.

750 pc and remove the galactic rotation component using a value of 14.5 kms^{-1} kpc^{-1} for Oort's constant A. We now look for evidence for systematic expansion in the *residual velocities*.

For a uniformly expanding shell of bright-rimmed clouds the residual radial velocities after removing the contribution due to galactic rotation are given by the expression (Sridharan 1992)

$$|v_{res}| = v_{exp}(1 - \sin^2\theta/\sin^2\theta_{max})^{1/2} \quad (1)$$

where v_{exp} is the expansion velocity, θ the angular distance of a cloud from the center of the distribution and θ_{max} the maximum value of θ (radius of the shell). We take the location of the star HD206267 to be the center and θ_{max} is 1.2°. In Fig. 1 we have plotted the absolute value of the residual velocities against $a = (1 - \sin^2\theta/\sin^2\theta_{max})^{1/2}$. Clearly the velocities increase at higher a (center) as expected in the case of expansion. The straight lines shown given by equation 1, correspond to expansion velocities of 2 and 6 kms^{-1}. We conclude that the system of bright rimmed clouds in this region is expanding away from the star HD206267 at $\approx 4\, kms^{-1}$. The expansion age of the system works out to be 4 Myr.

4. Discussion

In this section we consider possible causes for this expansion such as stellar wind, radiation pressure and rocket acceleration. We also estimate the age of the HD206267 and make a brief comparison between the cometary clouds in the Gum-Vela region and the Cepheus region. We first estimate the energy and momentum of a typical cloud due to expansion. Reliable mass estimates are not available for all except one cloud. We use this single cloud mapped in CO by Duvert *et al.* (1990) as a guide to estimate masses for the other clouds. The size of this cloud is 1′ and the estimated mass is $18 M_\odot$. The average size of the clouds in our sample is 1.6′, ignoring the largest cloud with size 11′. Assuming the average densities for all the clouds to be the same we estimate the mass of a typical cloud to be $70 M_\odot$ and its momentum and energy (due to expansion) are 6×10^{40} gm cm s^{-1} and 1×10^{46} ergs respectively. In the rest of this section we make rough estimates for the momentum and energy available from the previously mentioned processes. We will take the average current distance between the clouds and the star HD206267 to be 10.4 pc corresponding to an angular separation of 0.8°. We will also assume that the effects of the processes have remained constant at the current level over the expansion age of the system.

4.1. *Stellar wind*

Direct data for stellar wind from HD206267 are not available. Therefore we assume a terminal velocity of 2900 kms^{-1} and a mass loss rate of $3 \times 10^{-6} M_\odot\, yr^{-1}$ believed to be appropriate for this star (the mass loss rate is likely to be considerably less than the assumed value: Drake 1990; Bieging, Abbot & Churchwell 1989). We find the total momentum intercepted by a globule over the expansion age of the system to be 6×10^{38} gm cm s^{-1}, which is less than the required momentum by a factor of 100, leading to the conclusion that stellar wind could not have caused the expansion.

4.2. *Radiation pressure*

The luminosity of an O6.5V star is $3 \times 10^5 L_\odot$ giving a maximum available momentum due to radiation pressure of $L/c = 4 \times 10^{28}$ gm cm s^{-1}. We estimate that a typical globule will acquire, over the expansion age of the system, a total momentum of 4×10^{38} gm cm s^{-1} which falls short of the required momentum by two orders of magnitude. We therefore conclude that the radiation pressure cannot be responsible for the observed expansion.

4.3. *Rocket effect*

We finally consider the rocket effect caused by anisotropic ablation of the clouds caused by ionising radiation impinging on the sides of the clouds facing the star (Oort & Spitzer 1955). Taking the mass loss velocity to be the same as the sound speed in the ionised bright rim (13 kms^{-1}; $T \approx 10^4$K), and the measured density of 100 cm^{-3} (Duvert *et al.* 1990), we estimate the total mass lost over the expansion age to be $11 M_\odot$. With the mass loss occurring at 13 kms^{-1}, the momentum imparted to the cloud is then 3×10^{40} gm cm s^{-1} compared to the required momentum of 6×10^{40} gm cm s^{-1}. Taking into account the fact that the clouds would have lost mass at a higher rate when they were closer to the star, it appears reasonable to conclude that the clouds have been accelerated to their present velocities by the rocket mechanism.

4.4. *Age of HD206267*

Using available photometry and stellar evolution models we make a rough estimate of the age of the star HD206267, classified as O6.5V. Using data from Humphreys (1978) we estimate the bolometric luminosity of the star to be -8.83. As extinction for this star itself is not available, we have used the average of the values for HD206267C & D ($A_v = 1.55$). The extinction values for the other stars in the region (Ceph OB2) are similar. We used a distance of 750 pc and a bolometric correction of -3.5 corresponding to the spectral type O6.5. Now using the stellar evolution models of Schaller *et al.* (1992) for Z = 0.02, we estimate that the ZAMS mass of HD206267 to be $\approx 40 M_\odot$ and its age to be a few million years. This age is in reasonable agreement with the dynamical age of the expanding system of globules. There is no estimate available for age of the HII region IC1396. Observations and modelling in this direction will be useful.

4.5. *Comparison with the Gum-Vela region*

We list below the characteristics of the cometary clouds in the Gum-Vela and the

Cepheus regions, derived from our previous study (Sridharan 1992) and the present results.

	Gum-Vela	Cepheus
Morphology	Well developed tails	Only broad extensions
Size of the distribution	140 pc	40 pc
Expansion	$12\,\mathrm{kms}^{-1}$	$4\,\mathrm{kms}^{-1}$
Expansion age	6 Myrs	4 Myrs
Energy source	O4f star (ζ Pup) + massive stars in the recent past + SNe	Single O6.5f star

The first three points indicate that the Gum-Vela cometary clouds are in a later stage of development compared to those in Cepheus. In spite of the similar dynamical ages the differences in the evolutionary stages are possibly due to the stronger sources of energy in the Gum-Vela region. In addition to the massive star ζ Pup, the Gum-Vela region may have had a more massive star near its center about half a million years ago which exploded as a supernova (Sridharan, Srinivasan & Ramachandran 1994), and the progenitor of the Vela SNR. A more detailed analysis of the two environments using the theory of Bertoldi & McKee (1990) may help clarify the matter.

5. Conclusions

Our study of the radial velocities of the bright-rimmed clouds in the Cep OB2 has given evidence for expansion of the system away from the star HD206267 at $\approx 4\,\mathrm{kms}^{-1}$. The expansion age is 4 Myrs. This implies that such expanding motions are prevalent in regions surrounding high mass stars. Rocket effect appears to be the most likely operative mechanism in these regions. In spite of their similar ages, there are differences between the Gum-Vela region and the Cepheus region which can possibly be understood in terms of the differences in their energising sources.

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