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ASTRONOMY AND ASTROPHYSICS

Ara OB1: A stellar association formed by the action of an energetic event?

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Summary. Neutral hydrogen (at $\lambda = 21$ cm) and carbon monoxide (at $\lambda = 2.6$ mm) line observations of the interstellar medium in the neighbourhood of the association Ara OB1 are reported. The observed H I distribution indicates the presence of an expanding structure. The total H I mass associated with such feature amounts to 4800 solar masses, and its momentum and kinetic energy are $\sim 4\ 10^4 M_{\odot}$ km s^{-1} and $3\ 10^{48}$ erg, respectively. The H I structure, 42 pc in diameter, expands at a speed of 10 km s^{-1}. A possible origin for the expanding H I structure, and a genetic link between such structure and Ara OB1 are proposed.

Key words: clusters: open, and associations – interstellar medium: bubbles – radio lines: 21-cm – stars: formation of

1. Introduction

The study of neutral hydrogen in regions where young stellar OB-associations are located, provides information on the interactions between young and massive stars and the interstellar ambient gas surrounding them. Previous H I 21-cm line studies (Menon, 1958; Raimond, 1966; Sancisi, 1974; Simonson and van Someren Greve, 1976; Herbst and Assousa, 1977; Assousa et al., 1977; Read, 1980) have established the existence of neutral hydrogen shells associated with some OB-associations. The number of such studies, however, is small. Consequently, they are of little help in trying to statistically disclose the nature of the connection between stars and gas.

Therefore, to overcome the lack of systematic H I studies in OB-associations, a long term project was undertaken at the Instituto Argentino de Radioastronomía.

In this paper we would like to report on a detailed study of neutral hydrogen in the region of the Ara OB1 association. This association is a southern and rather compact stellar group which covers an area of roughly one square degree, its nucleus being the open cluster NGC 6193 ($l = 336.^\circ7$; $b = -1.^\circ6$). The low density ionized gas of the low surface brightness nebula RCW 108, in which the association is embedded, was studied by Cersosimo (1982).

At almost two degrees northwest of the open cluster a spectroscopically peculiar Of star, HD 148937, is found. Such star is located within a large and nearly circular H II region, which is bounded by a thin dust shell (Westerlund, 1960). A physical interaction between the large H II region around HD 148937 and NGC 6193 was suggested by Bruhweiler et al. (1981).

Several signposts indicate that star-forming processes may still be going on in the area (Shaver and Goss (1970); Frogel and Persson (1974); Obscuring material, mainly identified as the dark clouds FS 332, FS 335 and FS 337 (Feitzinger and Stuwe, 1984), is seen towards the region.

Herbst and Havlen (1977) suggested that the overall dimensions and structure of the region could be a consequence of a supernova event. Since H II regions and supernova events are phenomena which strongly disturb their surroundings, and because both are very likely to produce, as a distinctive signature of their interaction with the interstellar medium, noticeable perturbations in the H I distribution, a neutral hydrogen survey of the Ara OB1 region was undertaken. Carbon monoxide was also observed over a limited area of the stellar association. In the present paper H I-21 cm line observations of Ara OB1 are presented, and a tentative evolutive scenario for the whole region is envisaged.

2. Equipment and observations

The H I observations were made using the 30 m-dish of the Instituto Argentino de Radioastronomia (IAR) at Villa Elisa (Argentina). The HPBW of this antenna is 34′ at 1420 MHz. The receiver was used in the frequency switching mode, the reference band being 1.2 MHz apart. The system temperature against cold sky was 85 K, and the velocity resolution employed was 2.1 km s^{-1}. The data were obtained integrating three minutes of time on each point on an l, b grid with a spacing of one degree in both coordinates covering the region defined by $332° < l < 340°$ and $-4° < b < 2°$.

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The brightness temperature scale was calibrated using standard procedures at the IAR. The velocity range covered by our observations spans from -110 to $110\,\mathrm{km\,s^{-1}}$ (throughout this paper, radial velocities will always be referred to the LSR). After removing a quadratic baseline, a typical r.m.s. noise in the corrected baseline is 0.1 K. The external temperature calibration is accurate to within 5%.

The carbon monoxide observations (^{12}CO) were obtained using the 1.2-m millimeter telescope of the Columbia University at Cerro Tololo. At 115 GHz its HPBW is 8'.7 and the single sideband system temperature is ~193 K. Observations were made in the frequency switching mode, the reference band being 5 MHz above the line frequency. Typical r.m.s. noise levels of 0.1–0.2 K were reached after 7–10 minutes of integration time with 100 KHz wide filters.

The temperature scale was calibrated using hot and cold loads held in front of the receiver horn and were corrected for atmospheric attenuation which was measured using tipping curves. A total of 19 points, distributed along a cross with arms oriented in galactic latitude and longitude, were observed.

3. Observational results

3.1. Neutral hydrogen

Assuming an optically thin H I, longitude versus latitude contour maps of neutral hydrogen column density [N(H I)] were constructed for velocity intervals $\Delta V\,\mathrm{km\,s^{-1}}$ wide, according to the equation,

$$N(\mathrm{H\,I}) = 1.823\ 10^{18} \int_{v}^{v+\Delta v} T_b(v)\,dv \ \mathrm{atoms/cm^2}, \qquad (1)$$

where $T_b(v)$ is the observed brightness temperature.

Two of such maps are shown in Fig. 1. The upper figure displays N(H I) in the velocity range -22 to $-14\,\mathrm{km\,s^{-1}}$ and the lower one in the velocity interval -10 to $-2\,\mathrm{km\,s^{-1}}$. Strikingly enough, each map shows a prominent H I structure (shadowed areas) westwards of the open cluster NGC 6193. In both figures dots indicate the main early type stars of NGC 6193, whereas the continuum peak at 5 GHz (Shaver and Goss, 1977) is marked by a filled triangle.

In Fig. 2 a series of twelve brightness temperature contour maps are shown on l, b diagrams. The radial velocity of each map is indicated in the upper right corner and contour levels are given in K. By inspecting such maps, besides the strong emission features present at $b=0°$, at lower latitudes one gets the impression to be looking at cross cuts through an expanding shell. The map at $-24\,\mathrm{km\,s^{-1}}$ displays a typical neutral hydrogen distribution, i.e.: strong features at $b=0°$, representative of structures on a galactic scale, and brightness temperature contour lines more or less parallel to the galactic plane. In the velocity range from -22 to $-2\,\mathrm{km\,s^{-1}}$ such distribution departs drastically from the previous one. At intermediate velocities, -18 to $-6\,\mathrm{km\,s^{-1}}$, a ring-like structure, characteristic signature of an expanding shell, is partially recognized. At extreme radial velocities, -22 to $-20\,\mathrm{km\,s^{-1}}$ and -4 to $-2\,\mathrm{km\,s^{-1}}$ respectively, regions tentatively associated with receding and approaching caps are envisaged. To derive the neutral hydrogen mass associated with the expanding feature, it is necessary to estimate the overall galactic hydrogen contribution. Such contribution, which varies in velocity and position, was computed for every map of Fig. 2 from regions with constant galactic longitude, located far enough

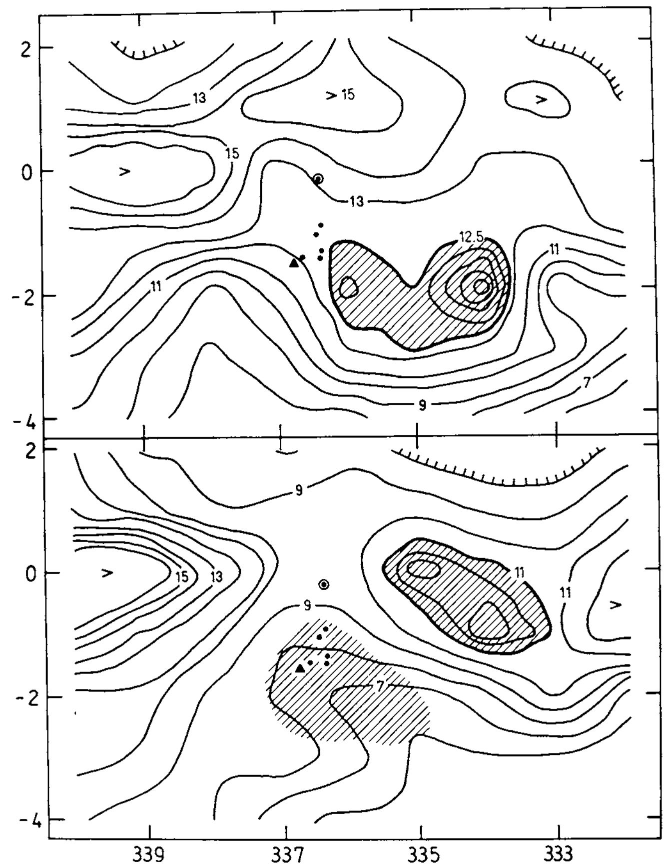

Fig. 1. Latitude-longitude neutral hydrogen column density contour maps, for the velocity range $-22 < V < -14\,\mathrm{km\,s^{-1}}$ (upper) and $-10 < V < -2\,\mathrm{km\,s^{-1}}$ (lower). The contour levels are in units of 1 10^{20} atoms/cm^2. The early-type stars of Ara OB1 are indicated by dots. An encircled dot marks the position of HD 148937. The compact H II region observed at 5 GHz by Shaver and Goss (1970) is marked by a filled triangle. The neutral hydrogen associated with the expanding feature is depicted by shadowed areas.

from the shell, at $l=332°$, 338°, and 339°. The neutral hydrogen associated with the expanding structure is indicated by a shadowed area in the individual maps of Fig. 2. It is very hard to ascertain whether the apparent lack of shell emission around $l\sim337°$ and $b\sim0°$ is real or not. There, the observed neutral hydrogen distribution is dominated by a feature centered at $l\sim339°.5$ and $b\sim0°$ originated in the general galactic structure of our Galaxy. This feature severely hampers and distorts the contribution of any H I which might be associated with the expanding feature. In Fig. 3 cross-cuts of the brightness temperature distribution across such shell are shown.

In Table 1 the main H I shell parameters are summarized. The shell centre has been derived as the centroid of the total shell column density distribution. Linear dimensions were derived from measurements carried out at different position angles from the shell centre. A typical error of such parameters amount to 10–15% of the quoted values in Table 1. The total H I shell mass was derived through planimetry of the shadowed areas seen in Fig. 2. While doing the integration of a given map, the "zero brightness temperature contour" of the expanding neutral hydrogen was set equal to the lowest contour level of the hatched region of such map, i.e.: in Fig. 2f) the "zero brightness temperature contour" is 75 K. To derive the volume density, the neutral hydrogen was assumed to be distributed in a spherical shell. The uncertainty in the derived value is high, at least a factor of two, thus reflecting our poor knowledge of the true spatial distribution. The systemic velocity of the H I shell, V_{sys}, was computed relying on two independent criteria. Firstly, by equating it to the radial velocity at which the central H I hole reaches its maximum angular dimensions; secondly, from a mass-weighted average radial velocity obtained from the observed H I mass-radial velocity distribution. Both estimates agree to within the uncertainties. Using V_{sys} and adopting the radial velocity field of Feitzinger and Spicker (1985), the expanding structure is placed at a kinematical distance of 1400 ± 200 pc. A lower limit to the expansion velocity was derived from $V_{exp} = V_{max} - V_{sys}$, where V_{max} refers to the maximum radial velocity, either approaching or receding, of the neutral hydrogen structure and V_{sys} has the same meaning as before. It is a lower limit because at extreme radial velocities the mass content of the H I caps is very low, henceforth its contribution is very difficult to pick up out of a complex and rapidly changing H I galactic background.

Within the shell, H I total column density increments as high as a factor of four are noticeably over an angular scale of one degree. The shell is obviously clumpy since a constant volume density can only account for total H I column density enhancements of a factor of two. The total momentum and kinetic energy of the H I shell are $\sim 4\ 10^4 D^2 M_\odot$ km s^{-1} and $\sim 3\ 10^{48} D^2$ erg, respectively, where D is the source distance in pc divided by 1400. These values are likely to be underestimates since not all the pieces of the shell may have been identified.

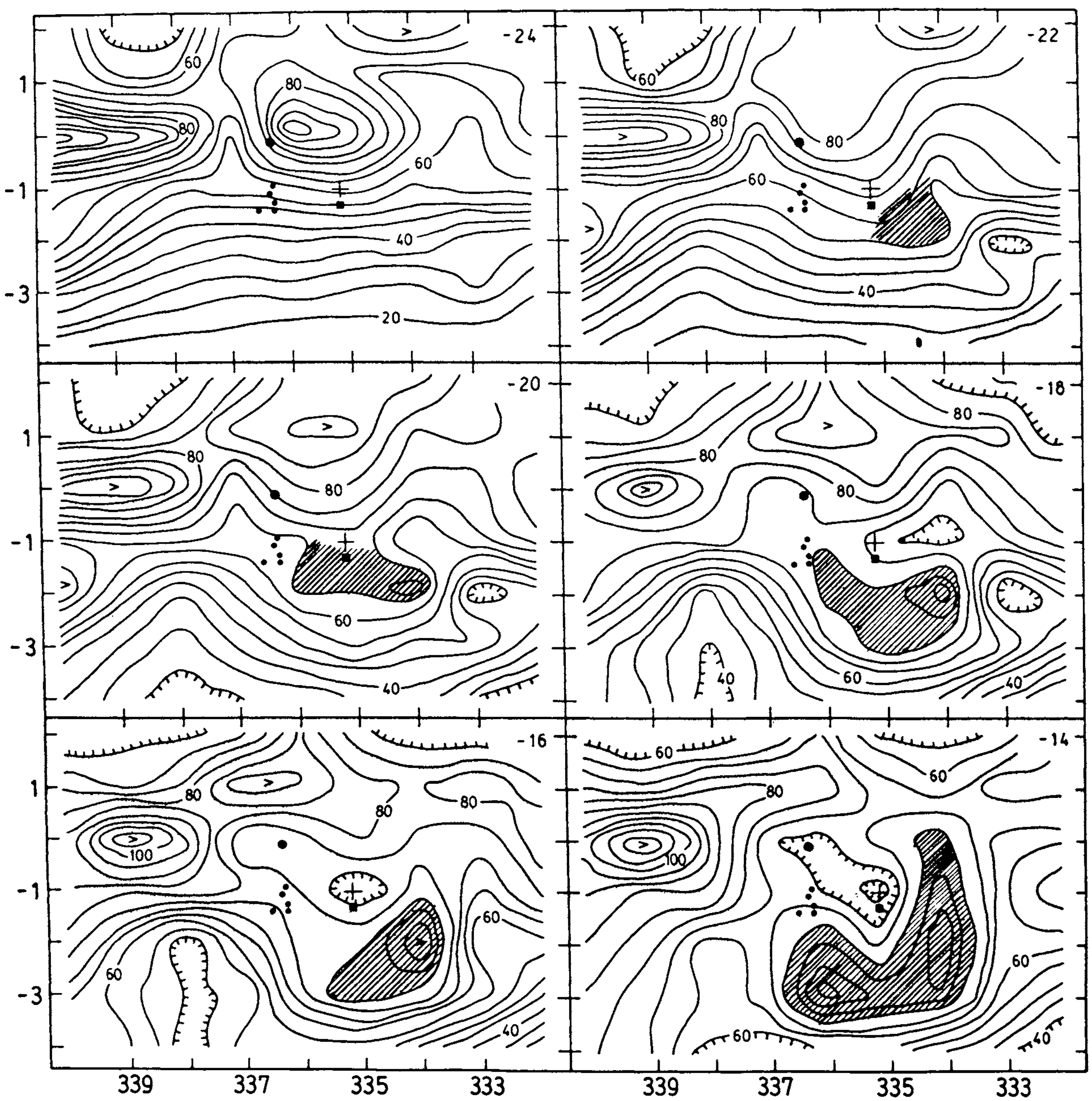

Fig. 2a–l. Latitude-longitude brightness temperature contour maps for the velocity range $-24 < V < -2$ km s^{-1} drawn each 2 km s^{-1}. The contour levels and in K and the contour spacing is 5 K. The radial velocity of each map is indicated in the upper right corner. The centroid of the H I distribution (shadowed areas) is marked by a plus sign, while the catalogued position of NGC 6167 is shown by a filled quare.

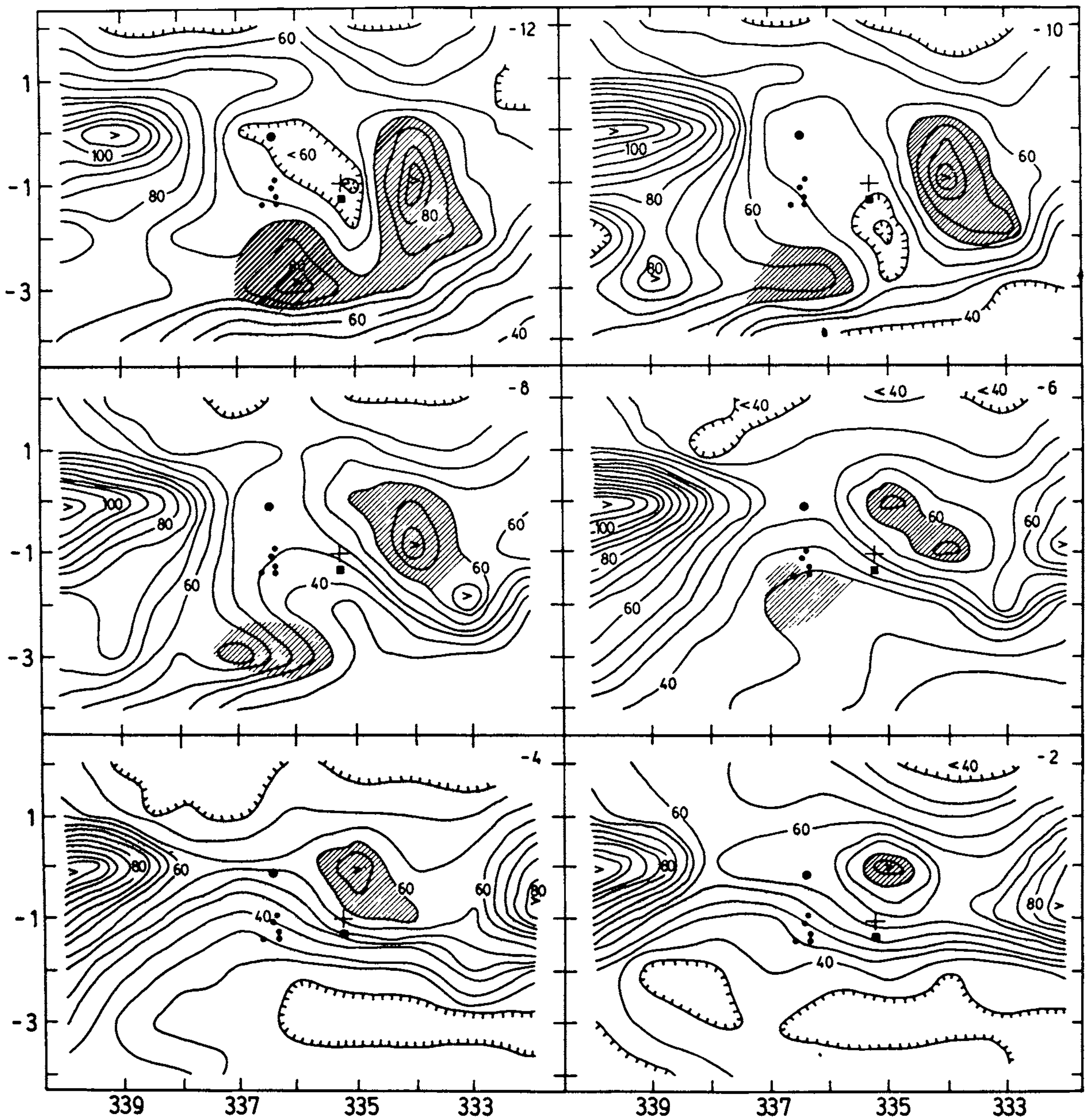

Fig. 2a–l (continued)

3.2. Carbon monoxide

Our limited sample of carbon monoxide data exhibits a very complex velocity field. Westwards (approximately 30′) of NGC 6193, CO profiles are single-peak attaining a maximum antenna temperature (typically between 3 and 6 K) at a radial velocity of $-22\,\mathrm{km\,s^{-1}}$. On the other hand, 40′ south of NGC 6193 double-peak profiles are observed, this time peaking at ~ -19 and $\sim -8\,\mathrm{km\,s^{-1}}$, respectively. To further complicate this picture, 1°4 eastwards of the open cluster single peak profiles are again observed, but now reaching a maximum intensity at $\sim -9\,\mathrm{km\,s^{-1}}$. Hence though our CO data are of little help in mapping the molecular material seen in the area, they clearly show there the presence of at least two molecular complexes having radial velocities of ~ -18 to $-22\,\mathrm{km\,s^{-1}}$ and -7 to $-9\,\mathrm{km\,s^{-1}}$, respectively.

By applying the velocity field of Feitzinger and Spicker (1985) one may fall into the temptation of deriving not only a kinematical distance for both molecular complexes, but also of concluding that both complexes are unrelated to Ara OB1, for along the line of sight toward $l \sim 336°$, radial velocities of -8 and $-19\,\mathrm{km\,s^{-1}}$, imply kinematical distances of ~ 1100 and ~ 2000 pc, respectively. Nonetheless, bearing in mind the complex velocity field shown by the neutral hydrogen, in our opinion such a straightforward interpretation is naive and very risky. To further emphasized our word of caution, we would like to bring up the optical evidence presented by Herbst (1974), in the sense that an ionization front formed by the early type stars of NGC 6193, is eroding a nearby

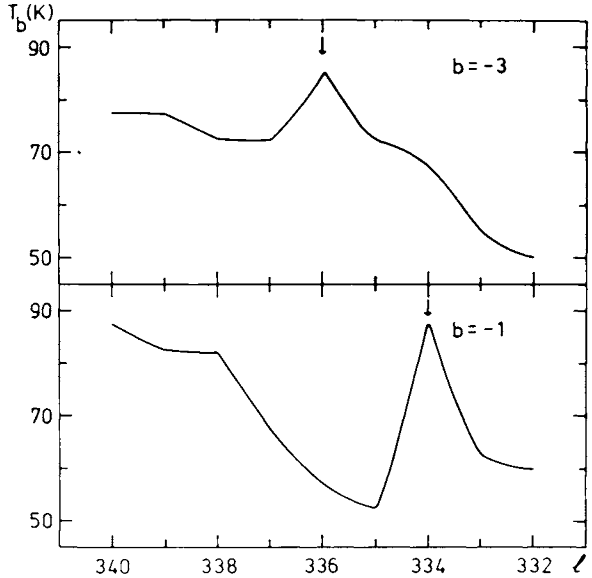

Fig. 3. Neutral hydrogen brightness temperature profiles for two galactic latitudes. The arrow marks the position of the H I shell

Table 1. Parameters of the H I expanding structure

Property	
Shell centre	$l \cong 335\overset{\circ}{.}5$; $l = \cong -1\overset{\circ}{.}1$
H I systemic velocity	-12 km s^{-1} (LSR)
Shell radius at peak brightness temperature[a]	~ 31 pc
Outer radius[a]	~ 48 pc
Inner radius[a]	~ 21 pc
Shell thickness[a]	~ 27 pc
Expansion velocity	~ 10 km s^{-1}
Total H I mass[a]	$\sim 4800\,M_{\odot}$
Mean H I volume density[a]	~ 0.5 atoms/cm^{-3}

[a] Assuming a distance of 1400 pc (this paper)

molecular cloud. We believe that such cloud has to be one of those detected at CO frequencies.

4. Discussion

*4.1. Ara OB1-*H I *structure. A causal relationship*

As a first step towards attempting to understand what could have happened in the region we should answer questions like: i) Is there any physical relationship among NGC 6193, the molecular cloud observed through carbon monoxide, the star HD 148937 and the expanding H I structure?; ii) Is there any clue about the mechanism responsible for the formation of the H I feature?.

Let us examine the first question. If a physical link among different kinds of objects is to be found, a necessary condition would be a similar distance for all of them.

According to a photometric study by Herbst and Havlen (1977) Ara OB1 and its central cluster (NGC 6193) are at a distance of 1320 ± 120 pc. To within the uncertainties, this distance agrees quite well with the kinematical distance derived for the H I shell, namely 1400 ± 200 pc.

Another strong argument in favour of a physical link between NGC 6193 and the molecular cloud seen in its neighbourhood, is provided by the bright rim structure making the interface between the H II region RCW 108 (see Herbst, 1974) and the R-association Ara R1 (Herbst, 1974, 1975). This R-association is embedded within the molecular cloud and has a distance modulus similar to Ara OB1.

In regard to HD 148937, only if its visual absolute magnitude M_v were in the range of -5.7 to -6.0 (case B of Bruwheiler et al., 1981) it would have a distance similar to that of the other objects. Therefore, purely based on distance arguments, and only if an extreme youth for HD 148937 is accepted, we may conclude that a physical interaction among the four main constituents of the region could be regarded as likely.

In attempting to answer the second question both age and geometric arguments will play a crucial role. Here a key point to be answered is the age of the H I shell. Unless the mechanism responsible for the expansion is known, only an upper limit can be obtained by assuming the constancy of the present day expansion speed. Thus an upper age of $2\ 10^6$ yr is derived. It should be realized that this age is obtained from a radius and an expansion velocity which are not precisely determined. Therefore the age estimate has an intrinsic uncertainty of perhaps a factor of two. To further illustrate the importance of an appropriate knowledge of the expansion mechanism and try to elucidate the origin of the expanding structure, let us consider two possible causes. On one hand, let us assume that the observed H I shell was created by the action of a strong stellar wind blown by a single massive star. Following Weaver et al. (1977) the bubble age will be $t = 6\ 10^5\ R/V \sim 1.3\ 10^6$ yr, where R is the radius of the shell in pc, and V is the expansion velocity in km s^{-1}. The wind power necessary to sustain such a bubble can be derived from

$$L = 6\ 10^{46}\ n\ R^5\ t^{-3}\ \mathrm{erg\,s^{-1}}, \qquad (2)$$

where both R and t have the same meaning as before, n is the ambient density in cm^{-3} and L is the wind power in arg s^{-1} (Weaver et al., 1977). It follows that $L = 6\ 10^{34}$ erg s^{-1}. This wind power implies mass loss rates ($\dot{M}$) in the range of 1 to $8\ 10^{-8}\ M_{\odot}$/yr. Such values are derived from the expression $L = 0.5\ \dot{M}\ V_w^2$, using lower and upper wind velocity limits (V_w) of 1500 and 4000 km s^{-1}, respectively (Garmany et al., 1980). From the empirical relation between mass loss rates and luminosities (Garmany et al., 1981), those $\dot{M}$ values correspond to $\log L/L_{\odot} = 4.1$–4.7, i.e.: to late O or early B-type stars. Therefore, it seems plausible that stellar winds blown by a single massive star could have created the expanding H I structure.

On the other hand, if a "typical" supernova explosion ("typical" meaning a SNR expanding within an interestellar medium having a number density of ~ 1 cm^{-3} and temperature 100–10000 K) was the main event giving rise to the expanding H I shell, an age estimate can be derived using the formula given by Chevalier (1974) for an SNR in its "snow-plough" phase,

$$R = 21.9\ t_5^{0.31}\ \mathrm{pc},$$

where R is the remnant radius and t_5 is its age in units of 10^5 yr. Using the R value quoted in Table 1 an age of only $\sim 1.0\ 10^5$ yr is derived. Thus, depending on the expanding mechanism at work, a quite different shell age is derived.

Admittedly both physical processes (either wind-bubbles or supernova remnants) are not so simply as stated above. It is well known indeed that most stars are born in groups (clusters or associations) and not isolated. Moreover, the most massive stars in such stellar groups will probably alter their surroundings before they begin to become supernova. Hence this "catastrophic" evolutive step along the life of a massive star may take place within a medium having a somewhat homogeneous density which has already been lowered, with respect to its "typical" interstellar value, by the action of powerful stellar winds blown by the supernova progenitor.

Certainly, the number of mechanisms capable of creating an expanding shell cannot be limited to the cases mentioned above. For example, a very interesting alternative is a collision of a high velocity cloud with the galactic disk (Tenorio-Tagle, 1981). In such mechanism an infalling cloud transfers a substantial fraction of its kinetic energy to the ambient gas in the disk. Although high velocity gas was observed in the area of Ara OB1 (Bajaja et al., 1985), such gas is likely to be part of a distant galactic arm (Bajaja et al., 1986). Therefore, this alternative will not be considered any further.

From here onwards, either stellar winds or a supernova event, will be assumed to have played a kew role in developing the expanding H I structure. If strong stellar winds was the starring mechanism, it would be very unlikely that the early stars of NGC 6193 could have developed such shell. Within the framework of the wind-bubble theory (Weaver et al., 1977), such stars are unable to match either the size or the expansion velocity of the H I structure. The excentric location of NGC 6193 (see Fig. 2) also conspires against such interpretation.

Ruling out NGC 6193, we call attention on the open cluster NGC 6167. Particularly, the spatial proximity between the H I centroid (plus sign in Fig. 2) and the cluster NGC 6167 (filled square in Fig. 2) is remarkable. NGC 6167 was studied by Whiteoak (1963) who concluded that "there is very little evidence of a main sequence of an isolated star grouping". Nonetheless, it must be emphasized that Whiteoak's data can only ruled out, owing to the limiting magnitude of his observations, the existence of an O-type cluster, but by no way can preclude the existence of an older one. This is in line with the work of Bruck and Smyth (1967) who, using photographic photometry down to visual magnitude 15.7, suggested that NGC 6167, if it is accepted as a genuine cluster, would be a star grouping about 4 10^7 yr old located at a distance of 1200 ± 200 pc.

Accepting the physical reality of NGC 6167, if its most massive main sequence stars were no earlier than B2–B3, they would have not reached the supernova phase yet, for the main sequence lifetime of such stars is roughly 4 10^7 yr (Stothers, 1972). In such a case, stellar winds blown by the most massive stars of NGC 6167 might explain what is observed in neutral hydrogen.

Though the above interpretation may be attractive to us, we cannot overlook as an alternative explanation, an energetic shock caused by a supernova explosion. Firstly, let us assume that in the past NGC 6167 was an O-type cluster, having as its most massive main sequence star an O7V. This star will release a stellar wind power of $\sim 1\ 10^{50}$ erg during its main sequence lifetime of $\sim 5\ 10^6$ yr. A similar amount of energy may be released during the subsequent Wolf-Rayet phase before ending its life as a supernova. At the end of the Wolf-Rayet phase using the equations of Weaver et al. (1977), and adopting an interstellar volume density of 0.5 cm^{-3} (see Table 1), the original O7V star could have created a bubble having a radius of 33 pc. Such bubble, developed at the end of the main sequence lifetime of the O7V star, has a radius already larger than the one actually observed nearby Ara OB1. Consequently it seems unlikely that a Type II supernova, representing a later stage along the evolutive path of an O-type star, could have played an important role in creating the expanding H I-shell.

Furthermore, based on the observed H I-shell systemic velocity, supernovae events arising from field stars placed, just by chance, along the line of sight towards NGC 6167, but unrelated to it, can also be discarded.

Therefore, ruling out supernova events we believe that strong stellar winds blown by the most massive stars of NGC 6167 remains as a viable alternative to explain the origin of the H I expanding feature.

Within the evolutive scheme proposed above, better age estimates for both open clusters (NGC 6193 and NGC 6167) are highly desirable. Reliable baricentral velocities for both clusters along with a spectral classification for NGC 6167 will show very useful in proving (or disproving!) our hypothesis.

Before ending this section we wish to point out, regardless of the origin of the H I expanding feature, that the observed shell thickness (~27 pc) cannot be reconciled with any theoretical predictions. For those cases explicitly dealt with in this paper, shell thicknesses roughly one tenth of the radius are foreseen. Therefore, the neutral hydrogen giving rise to the observed shell structure is very likely to represent swept up interestellar material, but by no way can be interpreted as the compressed gas layer predicted by theoretical models.

A more extensive study of this region in molecular transitions will be of interest and may help to disclose the relationship between Ara OB1 and its nearby molecular clouds. As a final remark we wish to state that reobservations of the region in the 21-cm line with improved angular resolution, as well as the use of a less subjective procedure to remove the overall galactic H I emission, will improve our knowledge of the H I shell parameters.

4.2. *Brief comparison with other* H I-*shells*

In the recent past quite a few H I shells, super-shells and shell-like objects have been reported both in our Galaxy and in external galaxies. Most of the galactic H I-shells or shell-like structures were reported by Hu (1981) and Heiles (1984 and references therein). From those works it is clear that there is no unique relationship between shells and any other type of astronomical objects (OB-associations included!).

For the sake of completeness, we shall briefly attempt to compare the Ara OB1 shell with those quoted by Hu and Heiles. When comparing the Ara OB1 H I shell with those reported by Heiles (1984) we find that the mass, radius, momentum and kinetic energy of the H I-shell reported by us are, on the average, a factor of 130, 10, 100, and 70 lower than the values quoted by Heiles. In obtaining the above factors only those shells located in the solar neighbourhood (closer than 4 kpc) were considered.

On the other hand, the high latitude shells reported by Hu (1981) seems to represent small scale disturbances located near the Sun. A very high percentage of such shells (78%) have diameters smaller than 25 pc. Moreover, most of the shells (75%) have kinetic energies under 1 10^{48} erg and 64% of the catalogued structures have H I masses smaller than 1000 solar masses.

To conclude, the most we can say is that the Ara OB1 H I-shell, in spite of what has been mentioned above, has some morphological and physical similarities with the most massive H I shells catalogued by Hu (1981), but it is a dwarf among giants when it is compared to those reported by Heiles (1984).

5. Conclusions

Observational evidence of a large and expanding H I structure located in a region nearby Ara OB1 has been presented. The kinematical distance of this feature (1400 ± 200 pc) agrees well with the photometric distance of both NGC 6193 (1320 ± 120 pc), which is seen in projection against the outer edge of the H I expanding structure, and NGC 6167 (1200 ± 200 pc) located at the center of the same expanding feature. This has led us to propose a genetic link among them. In our opinion the following chain of events may explain the observations: 1) after the birth of NGC 6167, about 4 10^7 yr ago, its most massive stars by the action of strong stellar winds gave rise to an interstellar bubble, 2) such bubble, while expanding, swept up interstellar material and slowed down, 3) the cold shell of swept up material run into an interstellar molecular cloud (one of those observed at CO frequencies), 4) as a consequence of 3, star formation was triggered in the molecular cloud, and 5) this chain of events ends up in the formation of Ara OB1 less than 2 10^6 yr ago.

Within our line of reasoning, NGC 6193 (or Ara OB1) can be taken as a fine observational example of a star-forming region triggered by the interaction of an external agent (the expanding H I-structure) with an otherwise normal interstellar cloud (the one associated with NGC 6193).

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