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# Interaction of the Supernova Remnant HB3 with the Ambient Interstellar Gas

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**Abstract**—The well-known shell supernova remnant (SNR) HB3 is part of a feature-rich star-forming region together with the nebulae W3, W4, and W5. We study the H I structure around this SNR using five RATAN-600 drift curves obtained at a wavelength of 21 cm with an angular resolution of $2'$ in one coordinate over the radial-velocity range $-183$ to $+60$ km s$^{-1}$ in a wider region of the sky and with a higher sensitivity than in previous works of other authors. The spatial–kinematic distribution of HI features around the SNR clearly shows two concentric expanding shells of gas that surround the SNR and coincide with it in all three coordinates ($\alpha$, $\delta$, and $V$). The outer shell has a radius of 133 pc, a thickness of 24 pc, and an expansion velocity of 48 km s$^{-1}$. The mass of the gas in it is $\approx 2.3 \times 10^5\ M_\odot$. For the inner shell, these parameters are 78 pc, 36 pc, 24 km s$^{-1}$, and $0.9 \times 10^5\ M_\odot$, respectively. The inner shell is immediately adjacent to the SNR. Assuming that the outer shell was produced by the stellar wind and the inner shell arose from the shock wave of the SNR proper, we estimated the age of the outer shell, $\approx 1.7 \times 10^6$ yr, and the mechanical luminosity of the stellar wind, $1.5 \times 10^{38}$ erg s$^{-1}$. The inner shell has an age of $\approx 10^6$ yr and corresponds to a total supernova explosion energy of $\approx 10^{52}$ erg. 

Key words: *interstellar medium, gaseous nebulae, neutral hydrogen, supernovae and supernova remnants.*

## INTRODUCTION

The supernova remnant (SNR) HB3 (G132.6+1.5) is well known, since it is part of a rich star-forming region in the Cas OB6 stellar association together with the H II regions W3, W4, and W5. This SNR is commonly assumed to be physically associated with them. At radio wavelengths, it has a significant angular size ($\approx 80'$) and a shell structure, suggesting that its evolution time is fairly long. This SNR has been extensively studied in the continuum, infrared, X rays, and molecular lines (see Landecker *et al.* (1987) and references therein).

Neutral hydrogen in this region has been studied by several authors. The papers by Routledge *et al.* (1991) and Normandeau *et al.* (1997), who used the DRAO aperture-synthesis radio telescope with an angular resolution of $2'$ and $1'$, are particularly noteworthy. Note, however, that Routledge *et al.* (1991) restricted themselves to a field of view of one primary beam (3° at the 10% level) with an angular resolution of $2'$ and a sensitivity of 1.34 K, so the sensitivity at the edges of the field deteriorated sharply during the data processing. Normandeau *et al.* (1997) had a rather poor sensitivity (3–15 K) and found nothing new in this region compared to Routledge *et al.* (1991). Note also that Routledge *et al.* (1991) gave a brief review of the then available observations of HB3 in the radio, X-ray, and optical ranges and in molecular lines.

In the period 2001–2004, we obtained five drift curves through the SNR HB3 in the HI line on the southern sector of the RATAN-600 radio telescope in a region that was twice that in Routledge *et al.* (1991) and with a sensitivity that was a factor of 20 higher than that in Normandeau *et al.* (1997). We confirmed several conclusions of the former paper and found new features in the distribution of gas around the SNR.

Note also that the distribution of neutral hydrogen emission in the Galactic plane is highly nonuniform and rich in various features. It thus follows that searching for evidence of the physical association of HI gas with such objects as SNRs (i.e., evidence that this is not a chance projection) is not an easy task. In our case, however, the problem is simplified, since the SNR is an active expanding object, so this must also be reflected in the kinematics of the ambient gas. Unfortunately, many authors pay little attention to this circumstance and restrict their analysis to the distribution of gas only in the plane of the sky. The goal of our work is to search for expanding HI

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shells around the SNR, which manifest themselves as ringlike structures in the coordinate–radial velocity plane.

## INSTRUMENTATION AND TECHNIQUE

To study the distribution of interstellar neutral hydrogen in the region of the SNR HB3, we obtained five drift curves in right ascension at $0^\circ\!.6$ declination intervals in the range of declinations from $+61^\circ\!.25$ to $+63^\circ\!.75$ on the southern sector of RATAN-600 at lower culmination (an elevation of $17^\circ\!.3$). In this elevation range, the RATAN-600 antenna has an angular resolution of $2'\!.6 \times 65'$ and an effective area of about 900 m$^2$ (Esepkina *et al.* 1979). An uncooled HEMT amplifier (Il'in *et al.* 1997) was used at the input. The system noise temperature was about 70 K, the 39-channel filter-bank spectral analyzer had a channel width of 30 kHz (6.3 km s$^{-1}$), and the channel spacing was also 30 kHz (Venger *et al.* 1982). The system control, data acquisition, and primary data processing were performed with an IBM PC computer (Alferova *et al.* 1986).

The drift curve at each declination consisted of two series with three observations each obtained with a receiver tuning shift by half the channel width, so each drift curve had 78 spectral channels following at 3.15 km s$^{-1}$ intervals. This technique also allowed us to effectively eliminate the interference. On the averaged record, the mean square of the antenna temperature fluctuations in spectral channels was 0.2 K. In each series of observations, the antenna and instrumentation parameters were controlled using measurements of a series of reference sources (Venger *et al.* 1981). For the southern sector, we used 3C 147 and 3C 430.

We determined the parameters of features in each channel using a Gaussian fitting program and then attempted to establish a relationship between HI emission features at different radial velocities and at different declinations. This is the only procedure where a significant subjective factor could be introduced.

The measured parameters of HI features have the following errors. The radial velocity of an isolated medium-brightness HI feature is measured with an accuracy of no lower than 1 km s$^{-1}$. In certain cases, the accuracy deteriorates due to the difficulties in separating an object from the background or from adjacent features. Given the antenna calibration errors, the measurement error of the brightness temperature of the HI line is about 0.3 K, and the error in the estimated angular sizes in right ascension is $0^\circ\!.1$. In declination, the antenna resolution is much lower, and, therefore, the accuracy of measuring the angular sizes is lower. The accuracy of estimating the distances depends on the method of their determination and, in each case, must be considered separately. As a result, the accuracy of estimating the HI mass in an isolated cloud is no better than 0.5–1 order of magnitude.

## RESULTS OF THE OBSERVATIONS

Figures 1–5 show the $\alpha$–$V$ diagrams for each drift curve without elimination of the extended HI emission background. The latter was done to avoid the systematic errors that appear in any technique of eliminating an extended background. The declinations (1950.0) of the drift curves are indicated at the top. To save space, the drift curves are given only in a limited range of radial velocities, from about +9 to −100 km s$^{-1}$, and no zero lines of each curve are given. The radial velocity with respect to the Local Standard of Rest is indicated near each curve on the right. The spectrometer channel number and the antenna temperature scale are indicated on the left. Compact HI features in the SNR region were identified using linear interpolation, which, of course, can cause their antenna temperature to be slightly overestimated. In each figure, the upper curve represents the drift curve in the continuum at a frequency of 1420 MHz. The SNR is highlighted by dark shading; in the remaining part of the figure, the heavy vertical lines corresponding to the SNR boundaries at minimum brightness in right ascension were drawn. The same dark shading in some of the figures highlights the absorption line from bright thermal continuum sources (W3, W4).

The thin closed lines represent the results of our attempts to combine the HI features at adjacent radial velocities into single structures surrounding the SNR. In our opinion, two such structures are observed, outer and inner. The features of the drift curves pertaining to different structures are highlighted by shading of different densities. The presence of such ringlike ($\alpha$–$V$) structures generally reflects the expanding shells of gas around the object. The table lists the measured and calculated parameters of neutral hydrogen in these structures under the assumption that they are indeed expanding shells around the SNR. We adopt the distance to the HI shells, $3 \pm 1$ kpc, in accordance with their mean radial velocities and the IAU 1986 model of Galactic rotation (Kerr *et al.* 1986). The mean radial velocities that we obtained are very close to the optical velocities of the HB3 features inferred from the H$\alpha$ observations by Lozinskaya and Sitnik (1980), and the adopted distance corresponds to this work. We see that the HI distribution in the inner shell is highly asymmetric; therefore, the table gives two values of the HI density, separately for the eastern and western parts of the

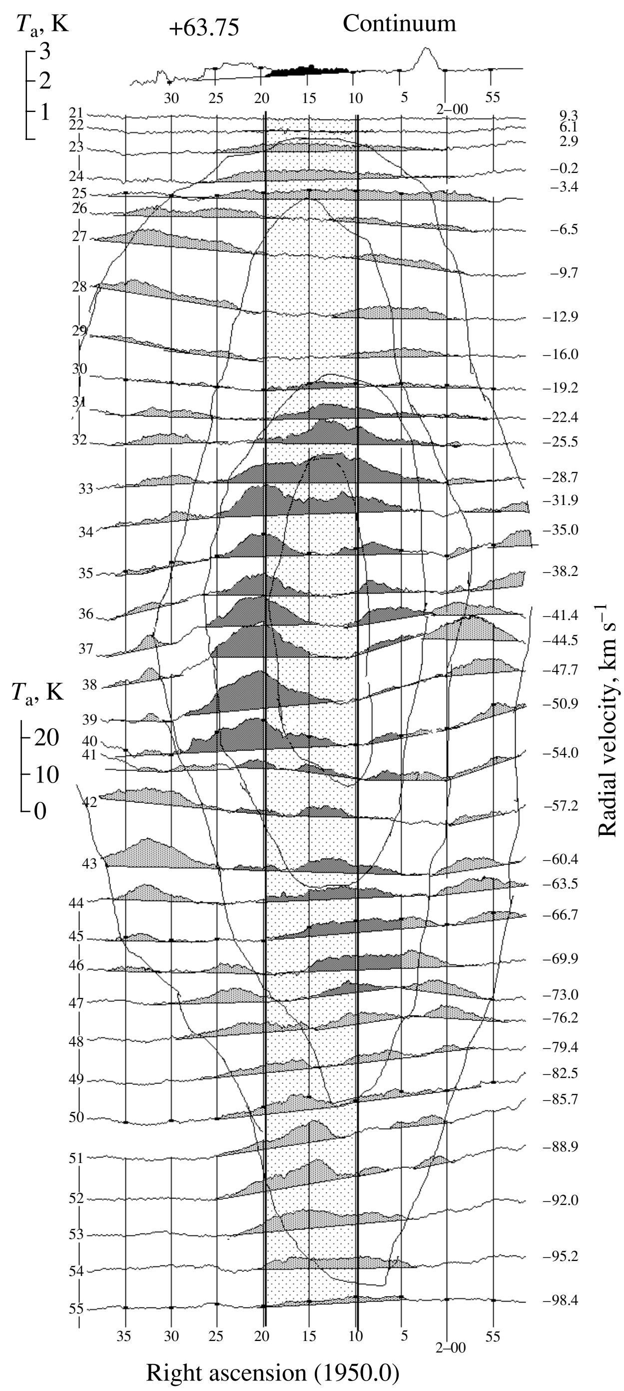


**Fig. 1.** Drift curves of the HI line emission in the region of the SNR HB3 at a declination of +63°75. The SNR continuum is highlighted by the black color on the upper curve. The radial velocities of each curve are given on the right. The gray shading marks the HI features that may be associated with the SNR.

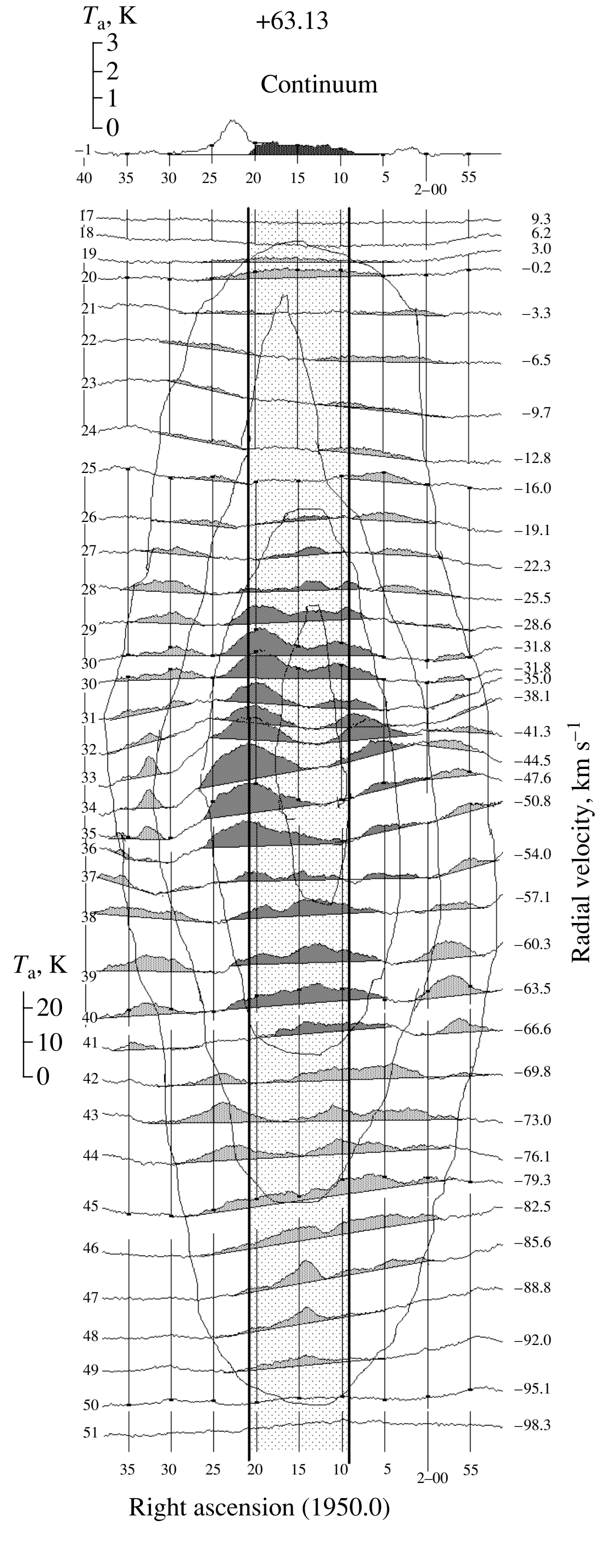


**Fig. 2.** Same as Fig. 1 at a declination of +63°13.

shell. The knife-edge beam of the radio telescope makes it impossible to estimate the size of the HI features in declination with an acceptable accuracy. However, it can be seen that the observed radial-velocity range of the HI ringlike structures decreases northward and southward of the central drift curve.

The simplest physical interpretation of the HI shell structure that we detected around HB3 is that the

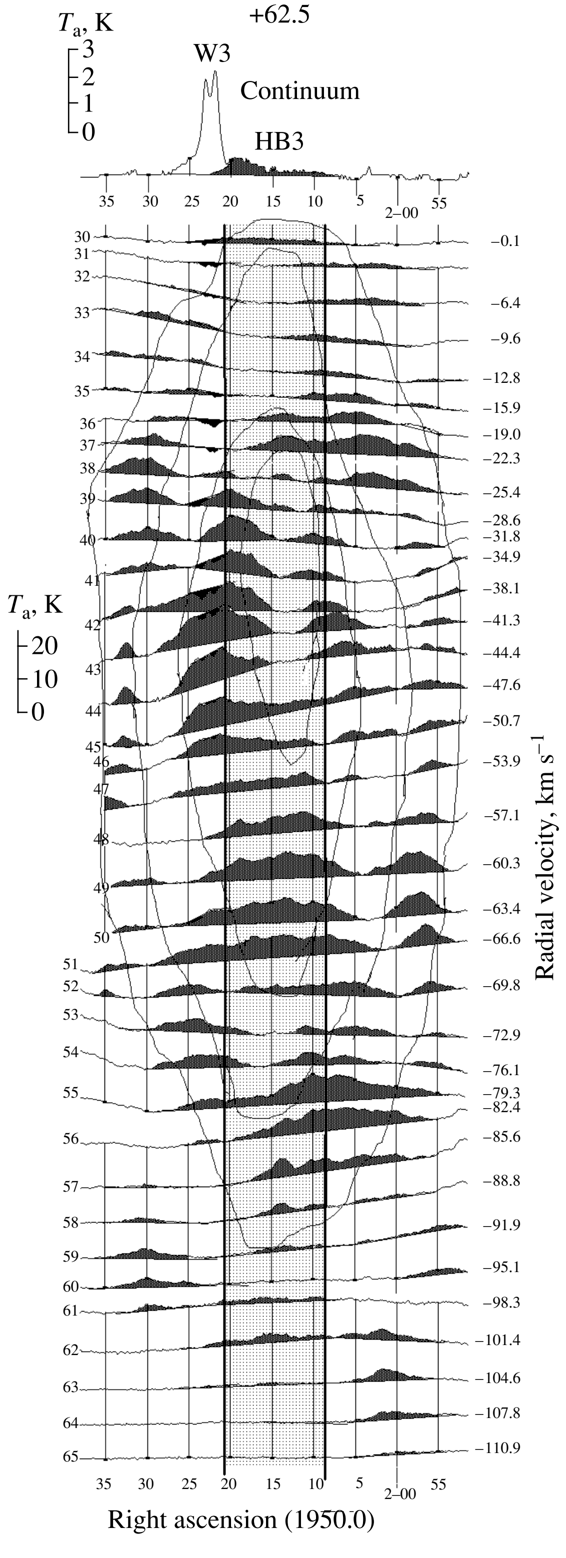

**Fig. 3.** Same as Fig. 1 at a declination of +62°.5.

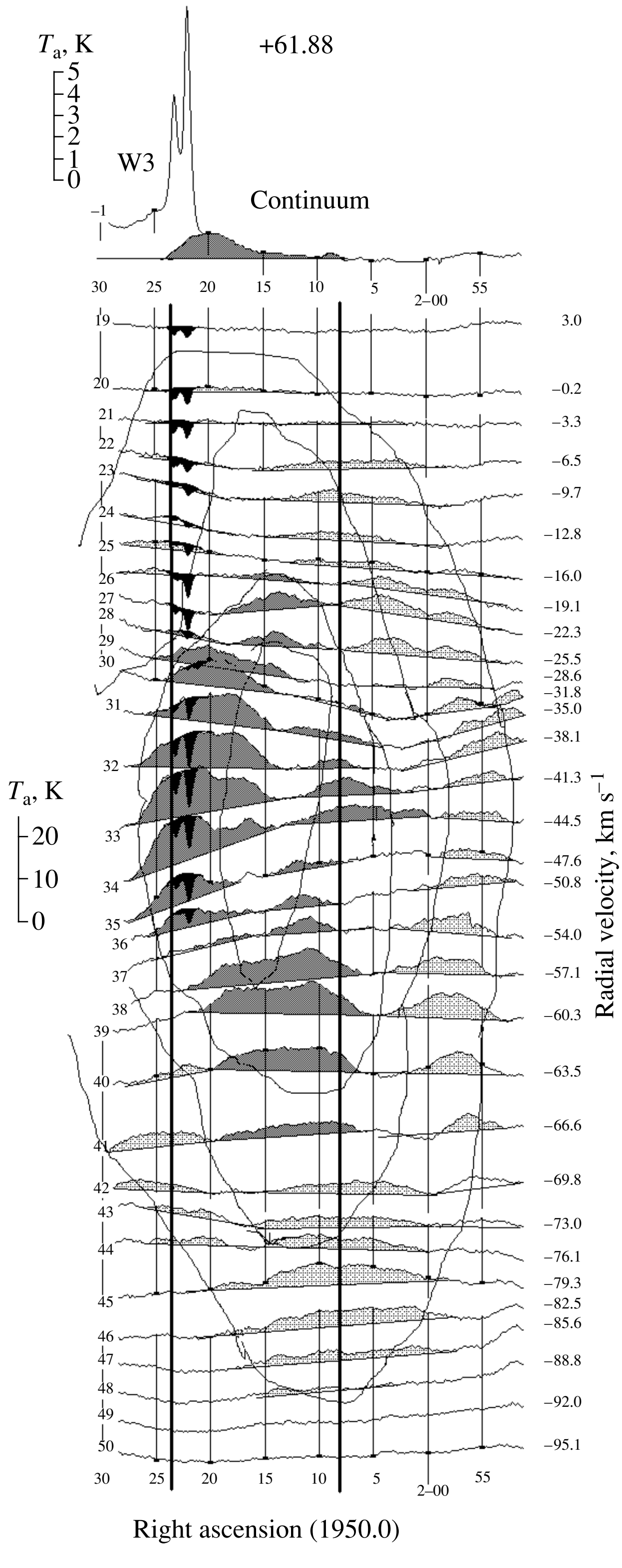

**Fig. 4.** Same as Fig. 1 at a declination of +61°.88.

outer shell may be assumed to be produced by the wind from the star over its lifetime on the main sequence, while the inner shell arose from the SNR shock. In this case, we can estimate several physical properties of the star and its explosion using theoretical estimates of the effect of shock waves from the

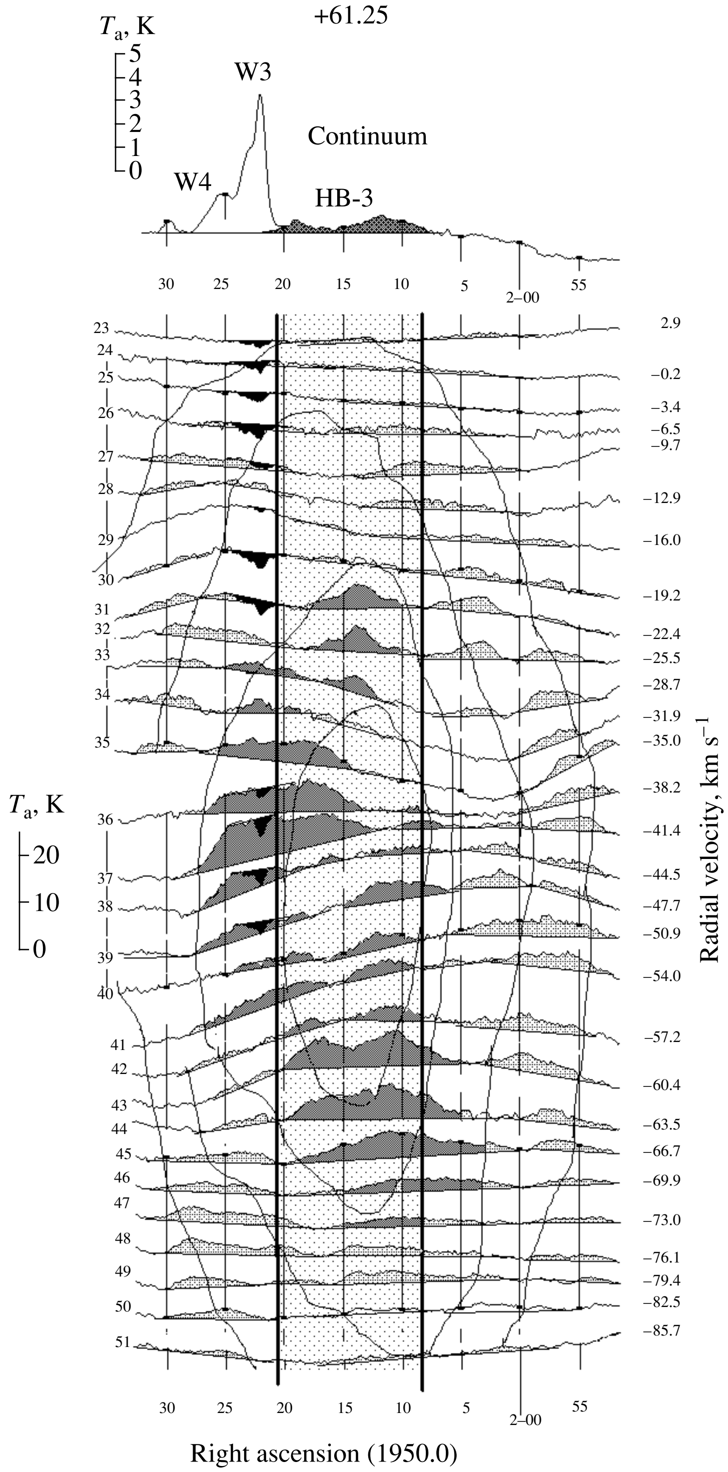


**Fig. 5.** Same as Fig. 1 at a declination of +61°.25.

stellar wind and SNRs on the interstellar medium. The initial density of the medium needed for such estimates can be obtained by "spreading" the total amount of gas in the shells over the entire current volume.

To estimate the mechanical luminosity of the stellar wind from the observed parameters of the outer shell, we can use the model by Weaver *et al.* (1977). Our estimations yield an age of the shell $1.7 \times 10^6$ yr and a mechanical luminosity of the stellar wind $1.5 \times$

Measured parameters of the HI shells

| Parameters | Outer shell | Inner shell |
|---|---|---|
| Coordinates | $\alpha = 2^h15^m$ | $\alpha = 2^h15^m$ |
| (1950.0) | $\delta = +62\overset{\circ}{.}5$ | $\delta = +62\overset{\circ}{.}5$ |
| Radial velocity, km $s^{-1}$ | −44.4 | −42.3 |
| Expansion velocity, km $s^{-1}$ | 47.5 | 24.3 |
| Distance, kpc | 3 | 3 |
| Outer radius, pc | 133 | 78 |
| Thickness, pc | 24 | 36 |
| HI mass, $M_\odot$ | $2.3 \times 10^5$ | $0.9 \times 10^5$ |
| HI density, $cm^{-3}$ | 2.1 | (E) 2.46<br>(W) 1.23 |
| Initial HI density, $cm^{-3}$ | 0.95 | 1.85 |

$10^{38}$ erg $s^{-1}$. At a typical stellar-wind particle velocity of $\approx 2000$ km $s^{-1}$, this mechanical luminosity requires a relatively high mass-loss rate, $6.8 \times 10^{-5}$ $M_\odot$ $yr^{-1}$, which is characteristic of massive O-type stars or M-type supergiants (de Jager 1984). It is well known that for Wolf–Rayet stars, the wind velocity can be several times higher; however, this stage is not too long and unlikely to play a significant role in forming the outer shell.

The kinematic parameters of the inner shell make it possible to estimate the parameters of the supernova explosion by using the model from Wheeler *et al.* (1980). The SNR age is $\approx 10^6$ yr, and the total explosion energy is $\approx 10^{52}$ erg.

## CONCLUSIONS

Thus, in the simplest model, our observations of the neutral-hydrogen distribution around the SNR HB3 have shown that, first, we see here the results of the explosion of one of the most massive stars in the Galaxy, and, second, the shells from the stellar wind and from the SNR shock are observed simultaneously. This case seems extremely rare, although traces of the action of the wind and the SNR were found in several other objects, and the model used may not be unique. Note that the presence of a dense inner HI shell around HB3 was also pointed out by Routledge *et al.* (1991), although these authors could not determine the full range of its velocities. In addition, they also pointed out traces of the outer HI shell, but failed to get its complete picture due to the limited field of view.

In general, our data may be considered to be consistent with the model of Routledge *et al.* (1991). However, the quantitative estimates of the shell age and energetics should be considered approximate, bearing in mind the semiquantitative nature of the gas-dynamical models of Weaver *et al.* (1977) and Wheeler *et al.* (1980) used for this purpose. However, energetics of this scale is now not considered as something extraordinary. It is rather difficult to estimate the effect of the wind from the stars of the Cas OB6 association on the kinematics of the outer HI shell surrounding the SNR HB3, since the SNR, although being close to the association, is nevertheless outside it (see Fig. 1 from Routledge *et al* 1991). As regards the inner shell, it probably has a much more complex structure than that assumed above in the simple model of two expanding HI shells. Nevertheless, all of the authors consider it to be the result of the action of the SNR shock on the interstellar gas. In our drift curves, especially at the southernmost declinations $+61\overset{\circ}{.}25$ and $+61\overset{\circ}{.}88$, we clearly see that the bulk of the HI is observed in the eastern and close (to the Sun) parts of the shell (the radial velocities are negative with respect to the mean velocity of the object). Incidentally, according to Huang and Thaddeus (1986), it is here that a CO cloud is located. In the western and far (from us) parts of the HB3 shell, where the SNR radio brightness is very low, Routledge *et al.* (1991) placed the high-velocity features of gas detected, in particular, by Lozinskaya and Sitnik (1980) in their model. According to Lozinskaya and Sitnik, the high-velocity features have a very low mass. As regards the bulk of the H$\alpha$-emitting filaments, their expansion velocity obtained by Lozinskaya and Sitnik (1980), $\leq 35 \pm 25$ km $s^{-1}$, agrees well with our data on the expansion of the HI shell (see the table). The significant decrease in the density of the cold neutral gas in the shell around the SNR in its northwestern and farther (from the Sun) part is also confirmed by our data shown in Figs. 3–5. Probably, the regions of very hot gas responsible for the X-ray emission could be located there as well (Seward 1990). A strong nonuniformity of the distribution of interstellar gas in the region of the SNR HB3 and a significant amount of the molecular component dissociated by the shock could explain the rather strange mean initial densities that we obtained for the outer and inner shells.

Finally, note that we presented here the results of RATAN-600 HI observations around one of the 104 SNRs selected from the catalog of Green (1998). The HI survey around them has now been completed, and the data are now processed. Later, drift curves in the $\alpha$–$V$ plane similar to those presented here will be available on the Web page of the Special Astrophysical Observatory, Russian Academy of Sciences, for free use.

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