KINEMATICS AND MORPHOLOGY OF THE NEUTRAL GAS AROUND WR STARS: NGC 2359

J.R. Rizzo and J. Martin-Pintado

OAN, Aptdo. Correos 1143, E–28800 Alcalá de Henares, Spain

Abstract

NGC 2359 is an optical nebula excited by the powerful wind and the radiation of the Wolf-Rayet (WR) star HD 56925. (WR 7). Based on observations of the HI hyperfine structure transition at 21 cm and mm observations of CO, we have drawn the history of the interaction of HD 56925 with the surrounding neutral gas. The main sequence phase of this star has carved a huge HI bubble of about 50 pc, which is expanding at 12 km s^{-1}. On the other hand, the CO emission around the nebula shows signs of interaction with the radiation field and the stellar wind during a previous RSG/LBV phase and probably the WR phase. There is a region with rather hot (80 K) gas almost coincident with the optical nebula, surrounded by more opaque and dense molecular gas. We think that the gas is beeing excited by the radiation field of the star and by shocking produced during the expansion of the WR bubble. This region is a good candidate to make mm, sub-mm and infrared observations of spectroscopic lines to disclose the physical and chemical effects of the evolution of massive stars onto the interstellar medium.

Key words: stars: individual (HD 56925) – stars: Wolf–Rayet – stars: winds – ISM: bubbles – ISM: individual (NGC 2359) – ISM: kinematics and dynamics

1. Background and observations

During their lives, the massive stars inject large amounts of matter, energy and momentum into the interstellar medium (ISM). The Wolf–Rayet (WR) stage is characterized by a copious mass loss (typically 10^{-5} M$_\odot$ yr^{-1}) driven by a fast (about 2000 km s^{-1}) and chemically enriched stellar wind. García-Segura & Mac Low (1995) have modeled the evolution of the gas which surrounds massive stars, from the main sequence to the WR stage. They predicted the formation of multiple shells as a consequence of the different shockfronts inside the gas. Once the massive star finishes the hydrogen burning in its nucleus and becomes a RSG or LBV, its stellar wind suddenly becomes more dense, and a significant amount of the stellar mass is deposited into the ISM at velocities around 20 km s^{-1}. Very probably, the formation of the optical ring nebulae starts in this brief stage. When the star comes to a WR stage, the wind is accelerated to hypersonic velocities and rapidly reaches the RSG/LBV wind.

However, the effects of the WR phase in the neutral (neither atomic nor molecular) gas have not been easily detected. NGC 2359 is a very interesting object, and many aspects of which has been thoroughly studied in the recent years. This optical nebula is excited by the WN4 star HD 56925 (WR 7 in the catalogue of van der Hucht et al. (1988). The nebula is nearly spherical with several small enriched filaments inside. (Esteban et al. 1990). St-Louis et al. (1998) have found the 1–0 S(1) line of H_2 towards the southern border of the HII region, but they could not establish the nature of the excitation (fluorescence or shocks) of the H_2. Cappa et al. (1999) made a complete map of the ionized component at the 1465 MHz continuum, and traced the HI emission presumably connected with the nebula.

The goal of this paper is to look into the history of the interaction of HD 56925 and its surroundings. We have analyzed a region of 6°× 6° around NGC 2359 using the 21 cm–HI survey of Hartmann & Burton (1997) and studied the large scale interaction of HD 56925 in the O-phase with the ambient HI. We have also observed in Kitt Peak the morphology and kinematics of the CO J = 1 → 0 (115.271 GHz) and J = 2 → 1 (230.538 GHz) lines around NGC 2359 and determined the global physical parameters of the molecular gas.

2. The HI main–sequence bubble

Fig. 1 depicts HI column density (N_{HI}) maps as a function of the radial velocity, indicated at the top left corner. We have found a large expanding bubble roughly centered at the nebula and its exciting star, the Wolf-Rayet HD 56925. The systemic velocity of the bubble is ∼ 64 km s^{-1} and it is expanding at 12 km s^{-1}. At an assumed distance of 5 kpc, the bubble has a size of 70 × 37 pc and a HI mass between 700 and 2400 M$_\odot$. By simple estimates of energetics, ages and stellar wind parameters, we think that this feature is a wind-blown bubble produced by the O-progenitor of the WR star.

This HI shell is in geometrical coincidence with the IRAS shell reported by Marston (1996). Furthermore, the mass of gas predicted from the IRAS data falls within the HI estimates presented in Table 1. We estimate a dynamical time for the shell of 2.3 Myr and a kinetic energy of

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

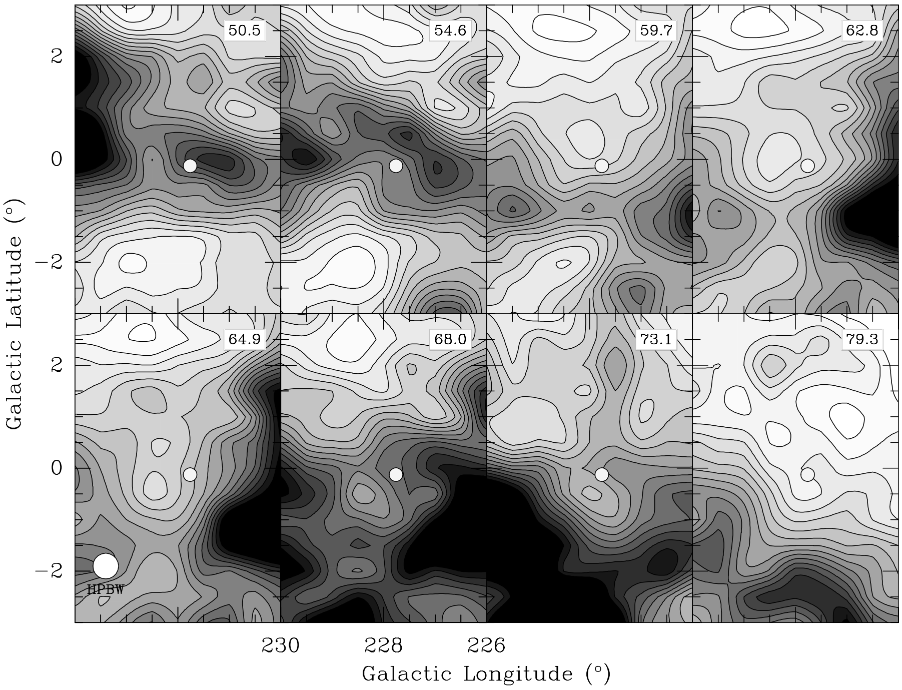

Figure 1. Distribution of the 21 cm–HI column density around NGC 2359, obtained from the survey of Dwingeloo. Every map has been constructed integrating over 2.1 km s^{-1}, around the central velocity indicated at the top right corner. Contour levels are 3 to 18 times 10^{19} cm^{-2}. The small circle near the centre points to NGC 2359.

2.2×10^{48} erg. This age and the kinetic energy associated to the HI shell clearly indicate that its origin is due to the main-sequence phase of HD 56925.

By adopting typical values for the mass-loss rate of 10^{-6} $M_\odot$ yr^{-1} and a wind velocity of 1000 km s^{-1} for the O–progenitor star, we estimate that this star deposited into the ISM during 2.3 Myr a total energy of $\sim 2.3 \times 10^{49}$ erg in the form of stellar wind. If this star has blown up the shell which we are observed in HI, it implies a kinematical efficiency of nearly 10%. Although the uncertainties in these computations are large and hard to be estimated, this value for the efficiency is in good agreement with the models that predict this type of structures (Weaver et al. 1977; Van Buren 1986) and reinforces our hypothesis of a main sequence origin of the HI shell.

3. CO morphology and kinematics

Fig. 2 shows the global spatial distribution of the CO J = 1 → 0 (left panels) and J = 2 → 1 (right panels) integrated emission for the three velocity components detected, hereafter named as Ambient 1 (A1, 35–38 km s^{-1}), Ambient 2 (A2, 64–69 km s^{-1}) and Broad component (B, 50–58 km s^{-1}). The CO emission for components A1 and A2 appear mainly to the east and to the south-east of the mapped regions, respectively. Although the spatial distribution for both components are found close in projection to the optical nebula, there is not a clear morphological correlation. Furthermore, there are no significant changes in the line widths and in the peak velocities over the regions where these components are observed. In contrast, the broad component B is observed in clear correlation with the eastern and the southern edges of NGC 2359, and with broader profiles, varying from 4 to 5.5 km s^{-1} wide. The most intense CO emission of component B is located beyond the outer edge of the HII region in NGC 2359, mainly to the south-east part, but also significant emission in the J = 2 → 1 line is detected towards locations projected on the HII region (middle right panel in Fig. 2).

The component B have slightly different peak velocities as a function of the position. Fig. 3 shows four position-velocity diagrams, taken in the directions sketched in the map at the top left corner. Slice 1 shows the most intense part of component B at 53–54 km s^{-1} and the western border of the component A2. A small velocity gradient in the component B is depicted in the slice 2, where we find a velocity shift of $\sim$ 2 km s^{-1}. Both slices 1 and 2 remark the spatial coincidence between the eastern border of component B and the western border of component A2. Slice 3 shows the presence of a weak “bridge” in the CO emission connecting the components B and A2. Slice 2, parallel to the slice 3 but 1′ to the north-east, does not show signs of this “bridge”, indicating its small size.

We have estimated the physical parameters of the molecular gas from the CO line emission by applying the LVG method. The main results derived for the three components are shown in Table 1.

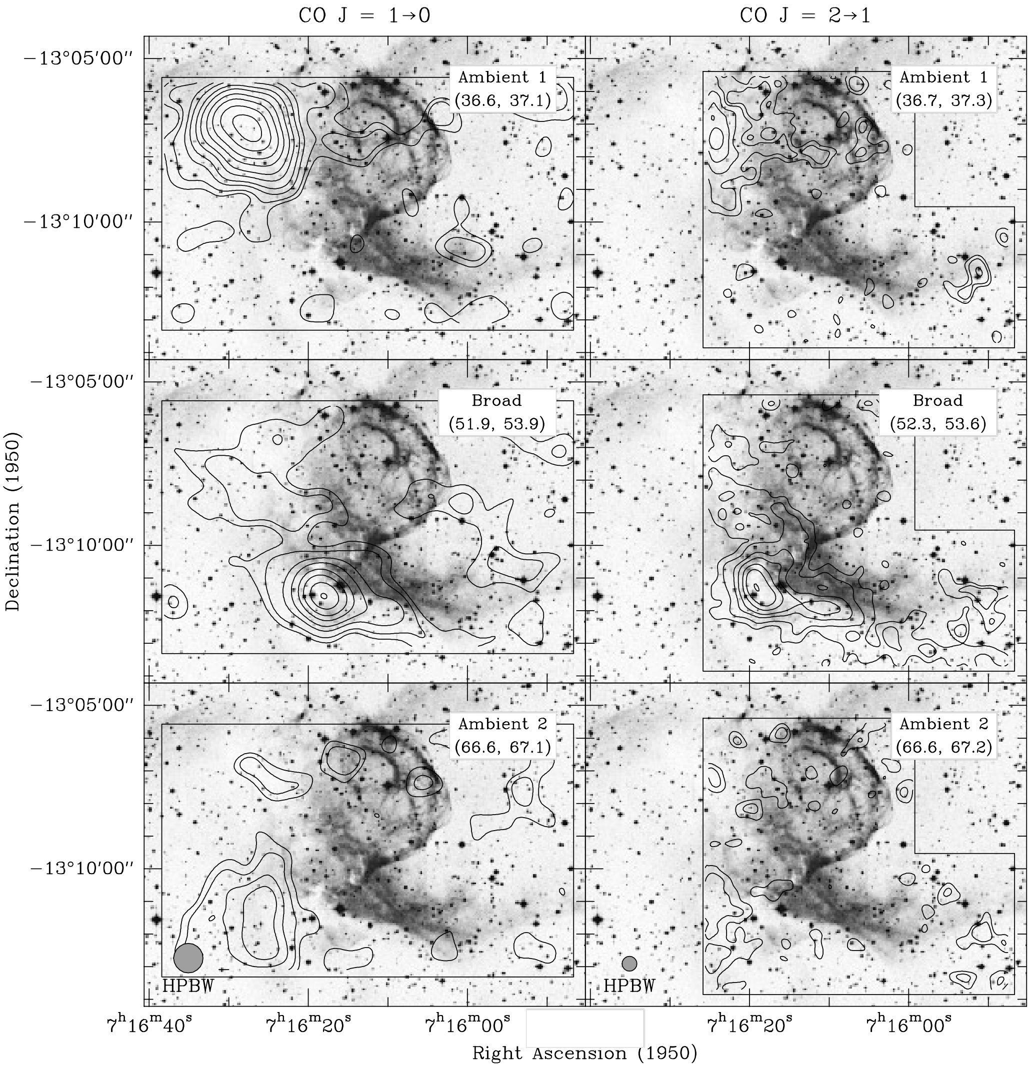

Figure 2. CO emission in the field of NGC 2359. The three maps at left correspond to the $J = 1 \rightarrow 0$ line, while the three maps at right correspond to the $J = 2 \rightarrow 1$ line. The three components detected are indicated at the top right corner of every map, together with the velocity of integration in km s^{-1}.

Table 1. Physical parameters of the CO emiting regions

Comp.	$\frac{2\rightarrow1}{1\rightarrow0}$	T_{ex} K	$n(H_2)$ 10^3 cm^{-3}	N(CO) 10^{16} cm^{-2}	$m(H_2)$ $M_\odot$
A1	0.5	5	0.6	1.0	96
A2	0.5	6	1.0	0.4	28
B_{all}	0.8	8	1.8	0.5	160
B_{HII}	2.0	$\gtrsim 80$	< 1.6	0.1	$\lesssim 8$

All the observational findings can be explained in a scenario in which a shock of 10–14 km s^{-1}, driven by the expanding hot bubble, impacts on the component A2. As a consequence of the shock, the gas was accelerated up to the velocities of the component B. The large width of the component B when compared with the component A2 can be understood by means of an increase of the turbulent motion due to the energy injected by the shock. Furthermore, the systemic velocity of the HI shell found at larger scales (presumably near the rest velocity of the gas) is also similar to the velocity of the component A2, supporting this scenario. This shocked region is small and it can not be spatially resolved in our data. Another crucial point is the weakness of the "bridge" which connects the components A2 and B. Higher angular resolution and more sensitive observations are needed to confirm the presence of the shocked layer and to fully study its properties. If this is the case, NGC 2359 would have the first direct evidence of shocked molecular gas in a WR environment. The optical nebula and its surroundings, where we find most of the CO emission, have a more recent origin than the large scale HI shell. The HII region has a size that indicate a dynamical age of less than 10^5 yr, comparable with the WR or a previous phase (Maeder & Meynet 1994).

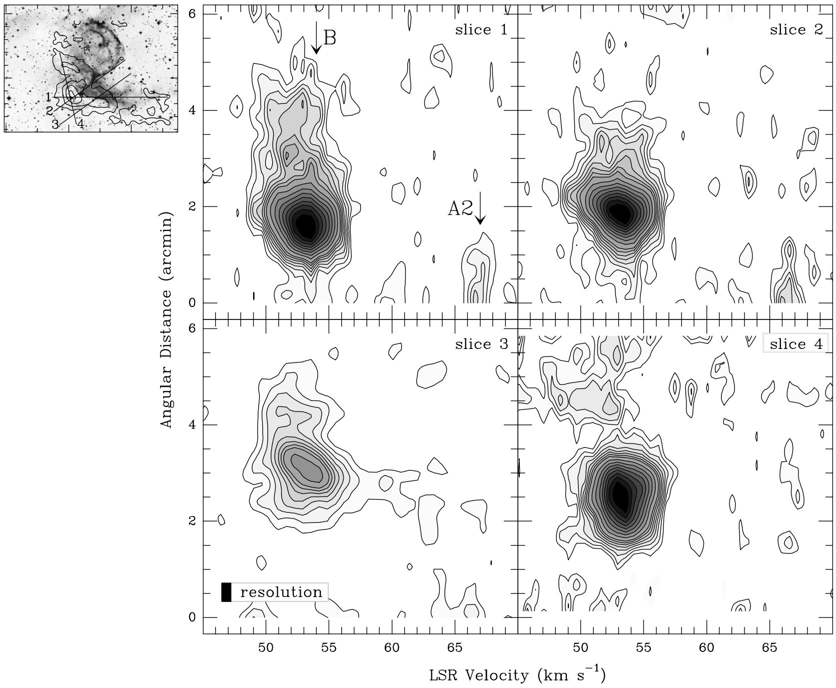

Figure 3. Four strips in position for the $J = 2 \rightarrow 1$ emission of CO. The location of the slices are sketched by right lines in the small map at the top left. The numbers indicate the slice number and the origin of the angular distance scale in the four slices.

Chemical studies using other molecular line transitions, especially those capable of tracing the molecular gas enriched by these phases, will definitively confirm or discard these ideas.

4. Conclusions

We have analyzed the large-scale 21 cm-HI emission in a $6° \times 6°$ field around the nebula NGC 2359, and found a large expanding bubble roughly centered at the nebula and its exciting star, the Wolf-Rayet HD 56925. The systemic velocity of the bubble is ~ 64 km s^{-1} and it is expanding at 12 km s^{-1}. At an assumed distance of 5 kpc, the bubble has a size of $70{\times}37$ pc and a HI mass between 700 and 2400 $M_{\odot}$. By simple estimates of energetics, ages and stellar wind parameters, we think that this feature is a wind-blown bubble produced by the O-progenitor of the WR star. The presence of a nearly spatially-coincident IRAS shell reinforces our hypothesis.

We have also mapped the CO J $= 1 \rightarrow 0$ and $2 \rightarrow 1$ emission adjacent to NGC 2359 and found three CO components in this region. Two of these components, with radial velocities of 34 (component A1) and 67 (component A2) km s^{-1}, have narrow profiles (up to 2 km s^{-1}) and do not show any morphological or kinematical effects which indicate the disturbance by the nebula or the WR star. However, the third component (the component B, emitting at 54 km s^{-1}), clearly bounds NGC 2359 at its southern and eastern border. The profiles are broad, with linewidths of 4–5.5 km s^{-1}. A velocity gradient of a few km s^{-1} is noted towards the south and south-eastern interface with the nebula. A weak "bridge" in velocity of small angular extension seems to connect this component with the component A2 at the southern part.

In view of the kinematics, the morphology and the physical properties of the CO, we think that the component A2 was shocked and accelerated by the expanding bubble to reach the radial velocities of the component B. The shock front is still acting at the southern part of the region. The origin of such shock might be related to the WR phase of HD 56925 or, more probably, to previous episodes of RSG of LBV.

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