A SUPERNOVA REMNANT COLLISION WITH A STELLAR WIND

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ABSTRACT

Numerical simulations of the interaction between supernova ejecta and a stellar wind are presented. We follow the temporal evolution of the shock fronts that are formed through such an interaction and determine the velocities, temperatures, and densities. We model the X-ray emission from the supernova remnant-stellar wind collision region, and we compare it with recent results from X-ray observations carried out with the Chandra satellite of the SMC supernova remnant SNR 0057–7226, which could be interacting with the wind of the Wolf-Rayet system HD 5980. The simulations predict the presence of shell-like regions of enhanced X-ray emission that are consistent with the presence of X-ray-emitting arcs in the Chandra image. Also, the observed X-ray luminosity is comparable to the X-ray luminosities we obtain from the simulations for a supernova with an initial energy in the \( 10^{50} \text{ ergs} \) range.

Subject headings: Magellanic Clouds — stars: individual (HD 5980) — stars: winds, outflows — supernova remnants — X-rays: ISM

1. INTRODUCTION

Massive stars are born, evolve, and end their lives in clusters. Massive stars, in general, possess fast and dense stellar winds that interact with their surroundings. Initially, the wind sweeps up interstellar material until the wind-blown bubble encounters a similar bubble produced by another nearby star, at which time an interaction between these two stellar winds takes place. These interactions occur at highly supersonic velocities, leading to diffuse emission at X-ray frequencies, as has recently been demonstrated both theoretically (Raga et al. 2001b; Cantó, Raga, & Rodríguez 2000) and observationally (Yusef-Zadeh et al. 2002) for the Arches cluster near the Galactic center. The most massive stars have very short lifetimes (\( \sim 10^6 \) yr) and they reach the supernova (SN) stage while all of the other stars are still on the main sequence or have just recently evolved beyond it. Thus, it is to be expected that when the SN occurs, the ejecta will encounter and collide with the stellar winds of the other massive stars within the cluster. These interactions should also be a source of X-rays. In this paper, we analyze the consequences of such collisions, and we apply the results to SNR 0057–7226 in the Small Magellanic Cloud (SMC) and its possible interaction with the stellar wind of the luminous blue variable/Wolf-Rayet (LBV/WR) binary system HD 5980.

HD 5980 is the most luminous point source in the Small Magellanic Cloud and is believed to consist of a close binary pair, both having Wolf-Rayet characteristics (Niemela 1988a) and a third, possibly line-of-sight O4–6 type component (Koenigsberger, Kurucz, & Georgiev 2002). Its eruptive mass-shedding events as well as the wind-wind interactions within the close pair have kept it under scrutiny for several years. HD 5980 is found at the edge of NGC 346, the largest cluster in the Small Magellanic Cloud. The age of the cluster is estimated at \( \sim 10^6 \) yr.

A nebulosity believed to be a supernova remnant lies on the foreground of HD 5980. This remnant might give rise to the +300 km s\(^{-1}\) component observed in the UV absorption lines toward HD 5980 (see Fitzpatrick & Savage 1980). This nebulosity, SNR 0057–7226, is associated with the X-ray source IKT 18 (Inoue, Koyama, & Tanaka 1983) that was confirmed to be a nonthermal radio shell by Ye, Turtle, & Kennicutt (1991), having a diameter of 3.2 pc (55 pc). It is the second most luminous SNR in the SMC at 843 MHz. An X-ray image recently obtained with Chandra (Názé et al. 2002) displays extended emission (130° × 100°; i.e., 39 × 29 pc) with a luminosity of \( 1.4 \times 10^{35} \text{ ergs s}^{-1} \) in the 0.3–10.0 keV band. The fact that the X-ray emission is centered on HD 5980 could well be a coincidence. However, UV and FUV observations (de Boer & Savage 1980; Koenigsberger et al. 2001; Hoopes et al. 2001) indicate that the portions of the SNR that are approaching the HD 5980 system have a different ionization balance than the opposite side (i.e., the side approaching the observer). These observational results could be explained if the receding portions of the SNR are interacting with the stellar wind from HD 5980. The analysis of this possibility is the primary motivation for undertaking the present study.

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2. MODEL FOR THE SNR–STELLAR WIND INTERACTION

2.1. The YGUAZÜ-A Code

For the numerical simulations carried out in this paper, we have used an axisymmetric version of the YGUAZÜ-A adaptive grid code, which is described in detail by Raga et al. (2000) and has been tested with laboratory explosion simulations (Sobral et al. 2000; Velázquez et al. 2001b) in SNR models (Velázquez et al. 2001a) and jets (Raga et al. 2001a). The gasdynamic equations are integrated with a second-order accurate (in space and time) implementation of the flux-vector splitting algorithm of Van Leer (1982), together with a system of rate equations for atomic/ionic species.

2.2. Initial Conditions and Assumptions

Due to the symmetry of the problem given by the axis that is joining the location of the SN explosion with the position of the star, we perform the integration of the cylindrically symmetric gasdynamic equations. A four-level binary adaptive grid with a maximum resolution of $1.46 \times 10^{17}$ cm was employed in a $50 \times 25$ pc (axial × radial) computational domain.

For the initial conditions, several assumptions are possible: (1) the SNR and the stellar wind are turned on simultaneously, (2) the stellar wind is already present when the SN explodes, or (3) the SN explodes first, and then the stellar wind is turned on. We assume that the SN explosion and the stellar wind are turned on at the same time.

Simulations can be carried out varying all of the different parameters of the calculation (terminal wind velocity, mass-loss rate, distance between the star and the SNR, energy of the SN explosions, interstellar medium density). However, we limit the present study to models with characteristics applicable to the HD 5980 system. Hence, in all simulations, we have fixed the stellar wind mass-loss rate at $\dot{M} = 5 \times 10^{-6} M_{\odot} \text{yr}^{-1}$, which is typical of massive O-type stellar winds. The wind-shedding star is located at $3 \times 10^{19}$ cm from the origin of the coordinate system, while the center of the SNR is located at $8 \times 10^{19}$ cm. Thus, the separation between the pre-SN and the normal star is of $5 \times 10^{19}$ cm. The calculations were initialized considering that the radius of the initial remnant is $4 \times 10^{18}$ cm. The density of the homogeneous interstellar medium (ISM) into which the SNR and the stellar wind are expanding is assumed to be of $1 \text{cm}^{-3}$, while its temperature is $10^4 \text{K}$.

Five numerical simulations were carried out considering different values for the initial SN explosion energy, $E_0$, and the terminal velocity of the stellar wind, $v_{\infty}$. These numerical models are labeled A to E and are listed in Table 1. The different values of $E_0$ are $10^{50}$, $5 \times 10^{50}$, and $10^{51} \text{ergs}$, while the values of $v_{\infty}$ are $1500$ and $2500 \text{km s}^{-1}$. Columns (2) and (3) of Table 1 list the values of these parameters as they correspond to each model.

In order to compare our numerical simulation with Chandra observations, we have computed X-ray emission maps for the $0.3–10 \text{keV}$ photon energy range, using the CHIANTI atomic database (Dere et al. 2001). For the calculation of the X-ray emission coefficient, we have assumed a modified Shull ionization equilibrium (Shull & van Steenberg 1982; Arnaud & Rothenflug 1986; Landini & Monsignori Fossi 1991) and that all of the excitation is in the low-density regime. (In this case, the emission coefficient is proportional to the square of the density.) The abundances for heavy elements were taken from the fit to the X-ray spectrum by Nazé et al. (2002), i.e., $Z = 0.17 Z_{\odot}$.

The CHIANTI database and associated IDL procedures are freely available at the following addresses on the World Wide Web: http://wwwsolar.nrl.navy.mil/chianti.html, http://www.arcetri.astro.it/science/chianti/chianti.html, and http://www.damtp.cam.ac.uk/users/astro/chianti/chianti.html.

### Table 1: Models and Simulated X-Ray Luminosities

| Model | $E_0$ (10$^{51}$ ergs) | $v_{\infty}$ (km s$^{-1}$) | $\tau$ (10$^5$ yr) | $L_X^{\text{snr}+w}$ (10$^{34}$ ergs s$^{-1}$) | $L_X^w$ (10$^{34}$ ergs s$^{-1}$) | Percent of $L_X^w/L_X^{\text{snr}+w}$ |
|-------|----------------------|--------------------------|-------------------|---------------------------------|-------------------------------|--------------------------------|
| A     | 0.1                  | 2500                     | 0                 | 7.9                             | 1.3                           | 16                             |
| A     | ...                  | ...                      | 10                | 5.6                             | 1.7                           | 30                             |
| A     | ...                  | ...                      | 20                | 3.9                             | 1.4                           | 35                             |
| A     | 0.1                  | 1500                     | 0                 | 5.7                             | 1.3                           | 23                             |
| B     | ...                  | ...                      | 10                | 3.8                             | 1.1                           | 28                             |
| B     | ...                  | ...                      | 20                | 2.6                             | 0.6                           | 22                             |
| C     | 0.5                  | 2500                     | 0                 | 44.3                            | 0.35                          | $8.6 \times 10^{-2}$           |
| C     | ...                  | ...                      | 10                | 43.2                            | 0.73                          | 1.7                            |
| C     | ...                  | ...                      | 20                | 37.8                            | 2.6                           | 7.0                            |
| D     | 0.5                  | 1500                     | 0                 | 44.3                            | 0.04                          | $8.6 \times 10^{-2}$           |
| D     | ...                  | ...                      | 10                | 42.2                            | 0.08                          | 0.18                           |
| D     | ...                  | ...                      | 20                | 34.4                            | 0.17                          | 0.5                            |
| E     | 1.0                  | 2500                     | 0                 | 78.0                            | ~0                            | ~0                             |
| E     | ...                  | ...                      | 15                | 93.0                            | 1.0                           | 0.8                            |

*a* $\tau = t - t_0$, where $t$ is the time and $t_0$ is the time at which the interaction between the SNR and the stellar wind bubble first occurs.

*b* X-ray luminosity from SNR plus the stellar wind and its interaction.

*c* X-ray luminosity from the interaction region and stellar wind only.
3. RESULTS

3.1. Evolution of the Collision between an SNR and a Stellar Wind

Figure 1 shows a comparison between the density evolution for model A (right) and model E (left). The top panels (for $t = 8000$ yr and $t = 17,000$ yr) represent the density distributions at the time when the encounter between the SNR shock wave and the stellar wind first occurs. The spherical shell located on the left-hand side is the windblown bubble surrounding the star. Note that there is a difference of more than 2 orders of magnitude between the density in the windblown bubble and the stellar wind that it encloses due to the fact that the stellar wind has swept up material from the interstellar medium into which it is flowing. As expected, the more energetic SN results in a remnant that expands and reaches the wind of the star sooner (model E, 8000 yr) than the less energetic SN (model A, 17,000 yr).

Once the SNR shock wave has reached the windblown bubble, two secondary shock waves are produced, one propagating into the remnant (S1) and the second one in the direction of the star (S2), sweeping up the material in the windblown bubble and in the stellar wind. This is illustrated in Figure 1 (top to bottom), which present the density evolution at temporal intervals of 5000 yr. The secondary shock wave that is propagating into the SNR material (S1) is almost spherical, unlike the shock wave that is moving into the stellar wind (S2), which initially presents a wavy structure that subsequently evolves into finger-like features. The propagation of these finger-like structures is clearly seen in model E, in which the evolution occurs more rapidly than in the lower energy SN models. At $t \sim 23,000$ yr (bottom left panel), these structures have reached the opposite side of the windblown bubble. The eventual fate of the windblown bubble is that only a small portion lying close to the symmetry axis of the interaction remains, while the rest will have been swept up by the SNR. As the SNR advances into the stellar wind, the S2 shock adopts the shape of a bow shock, enveloping the star. The bottom left panel of Figure 1 shows this structure very clearly (at $x \sim 3.5 \times 10^{19}$ cm).

The finger-like features are most likely produced by Rayleigh-Taylor (R-T) instabilities for the following reasons: the basic conditions for the onset of the R-T instability are the existence of two media with different densities, and an effective gravity with an orientation in the direction that goes from the high-density to the low-density medium. Both of these conditions are met in the interaction region. The gas behind the SNR shock wave is almost 2 orders of magni-
tude denser than the gas in the wind bubble, and a calculation of the gradient of the ram pressure across the interaction region for the $E_0 = 10^{51}$ ergs simulation at $t = 13,000$ yr yields an effective gravity at the location of the SNR/wind interaction region of $\approx 6 \times 10^{-4}$ cm s$^{-2}$, directed outward from the SN. Furthermore, using the values given above for the effective gravity and the density ratio and considering a typical size of $\approx 10^{19}$ cm for the initial perturbation (consistent with the radius of the wind bubble at the time when the wind/SNR interaction starts to take place; see Fig. 1), one obtains a $\gamma = 1.94 \times 10^{-11}$ s$^{-1}$ growth rate for the R-T instability. This growth rate is equivalent to a $\tau = 1600$ yr timescale, which is consistent with the time in which the finger-like structures develop in our simulation (which is smaller than the 5000 yr time intervals between the successive frames of Fig. 1).

The qualitative nature of the interaction does not depend significantly on the velocity of the stellar wind for values that are reasonable for O-type stars. As illustrated in Figure 2, the general features described above for the density evolution of the interaction also appear for a stellar wind having $v_\infty = 1500$ km s$^{-1}$ (Fig. 2, left; model B). The panels on the right of this figure reproduce the case with $v_\infty = 2500$ km s$^{-1}$ (model A). Figure 2 (top to bottom) displays the morphology of the interaction at temporal intervals of 10,000 yr, starting with initial contact between the SNR and the stellar wind.

An example of the kinematical characteristics of the flow that would be seen by an observer located along the symmetry axis in the positive $x$ direction is shown in Figure 3. Assuming that the observer is at rest with respect to the undisturbed environment of our simulations, the radial velocities of the absorbing (or emitting) gas are given by $v_{\text{obs}} = -v_x$ (where $v_x$ is the axial velocity of the flow). In this example, we present the velocity profile of the gas that lies along the symmetry axis at $t = 27,000$ yr for model A (see Table 1). The wind-shedding star is located at $x = 3 \times 10^{19}$ cm, and the portion of its stellar wind that is receding from the observer can be seen as the (cutout) maximum to the left of this position. The portion of its stellar wind that is approaching the observer is seen as the (cutout) minimum, just to the right of this position. The extension in the $x$ direction of this portion of the stellar wind is not as great as in the case of the receding wind, since it encounters the SNR ejecta (denoted as $a$ in Fig. 3). This encounter slows down the wind and leads to a shock wave ($S_2$, described above) having a velocity in the opposite direction (i.e., toward the star). It is interesting that even though the expansion velocity of the SNR is lower than the velocity of the stellar wind, the balance of the momentum is in favor of the SNR and the
interaction region has this net velocity toward the star. The velocity along the x-axis toward the star at position a is 120 km s\(^{-1}\), not too different from the radial velocity of high-ionization ultraviolet ISM components observed in absorption at 150 km s\(^{-1}\), corresponding to \(v_{\text{hel}} \approx 300\) km s\(^{-1}\) after subtracting the average systemic velocity for the SMC of \(\sim 150\) km s\(^{-1}\) (de Boer & Savage 1980; Koenigsberger et al. 2001) and the O\(\text{vi}\) components observed in the far-ultraviolet absorption components (Hoopes et al. 2001).

The shock wave that is moving into the SNR (S1) has a velocity of \(\sim -40\) km s\(^{-1}\) (denoted as b in Fig. 3) in the direction of the observer. In front of this shock, unperturbed SNR material is found, having velocities of 60 km s\(^{-1}\), decreasing systematically as the location of the progenitor of the SNR (at \(x = 8 \times 10^{19}\) cm) is approached, where \(v_x = 0\). The velocities between this point and the unperturbed ISM in the direction of the observer range from 0 to \(-150\) km s\(^{-1}\). Note that this latter velocity, when corrected for the average SMC systemic velocity (\(\sim 150\) km s\(^{-1}\)), lies at the velocity of the local (Galactic) ISM. Hence, the absorption features that may be produced in this region of the SNR (marked as c in Fig. 3) would be superposed on the local Galactic ISM absorptions and, thus, would be very difficult to observe.

If we assume a systemic velocity of \(v_{\text{snr}} \approx 188\) km s\(^{-1}\) for the SNR (Koenigsberger et al. 2001), the absorption components generated by our models at the opposite sides of the SNR (locations a and b in Fig. 3) would be observed at \(v_{\text{hel}} = (+120 + 188)\) km s\(^{-1}\) = +308 km s\(^{-1}\) and \(v_{\text{hel}} = (-150 + 188)\) km s\(^{-1}\) = +38 km s\(^{-1}\), thus suggesting that the pair of lines corresponding to the SNR that were observed by Koenigsberger et al. (2001) are really the \(v_{\text{hel}} = (+313, +33)\) km s\(^{-1}\) pair.

### 3.2. Simulated X-Ray Emission

For all of the numerical models, we have obtained simulated X-ray emission maps. For each of these maps, we have calculated total X-ray luminosities within the 0.3–10 keV band at different times, and these results are summarized in columns (5) and (6) of Table 1. The time for which the calculation is made is listed in column (4). The first time corresponds to initial contact between the SNR and the stellar wind. The second and third times correspond in all cases, except for model E, to 10,000 and 20,000 yr after initial contact. In the case of model E, the calculation was made at 15,000 yr.

The relative orientation of the SNR/wind collision region with respect to the observer is an important parameter for the calculation of the spatial distribution of the X-ray emission, and we shall discuss this below. For the moment, however, we shall concentrate on the case in which the angle between the x-axis of our calculations and the line of sight to the observer is 0°, i.e., the observer is situated on the extreme right in Figures 1 and 2 and therefore views the interaction region face-on.

The top panel in Figure 4 displays the X-ray emission at the time of initial contact between the SNR and the stellar wind for model A. Superposed on the emission arising in the SNR as a whole, two zones of higher intensity X-ray emission can be identified: (1) the rim of the SNR, where the mass density is high due to the swept-up ISM, and (2) a central dot that corresponds to the location of first contact between the SNR and the wind. The X-ray emission at this stage is dominated by the SNR. The total X-ray luminosity is \(7.9 \times 10^{34}\) erg s\(^{-1}\) in the 0.3–10 keV band, of which only \(1.3 \times 10^{34}\) erg s\(^{-1}\) arises in the shocked and unshocked stellar wind.

As time proceeds, the interaction between the SNR and the stellar wind involves more and more material, and the emission from the unperturbed SNR decreases. Thus, the relative contribution to the X-ray emission arising in the interaction zones becomes more significant. The second panel in Figure 4 illustrates the X-ray emission at \(t = 37,000\) yr, 20,000 yr after initial contact. The ring of intense X-ray emission that is visible in this figure corresponds to the regions of stellar wind that are making their first contact with the SNR. These regions have densities that are particularly high due to the presence of swept-up material (by both the SNR and the stellar wind). There is also a small ring near the center of the bright ring that, although significantly fainter, is visible in this same figure. This ring corresponds to emission from the bow shock that by this time has been formed, enveloping the star. The total X-ray luminosity at this time is \(3.9 \times 10^{34}\) erg s\(^{-1}\). Our simulations indicate that the combination of unperturbed stellar wind + shocked stellar wind contribute \(1.4 \times 10^{34}\) erg s\(^{-1}\) to this luminosity, i.e., 35% of the total X-ray luminosity.

Figure 5 presents the same results discussed above in relation with Figure 4, but for model E. The outer ring and the inner ring correspond to the interaction of the SNR with the ISM and the bow shock enveloping the star, respectively, as in Figure 4. In addition, the third ring (counting outward) is analogous to the bright ring in the lower panel of Figure 4, i.e., it corresponds to the first contact between previously unperturbed portions of the windblown bubble and the SNR. Because the SN in this example is more energetic, the evolution of the SNR/wind interaction takes place on
shorter timescales than in the example shown in Figure 4. Thus, the lower panel in Figure 5 displays features that have not yet formed at the evolutionary time illustrated in the lower panel of Figure 4. In particular, the second ring (counting from the inside) corresponds to the finger-like features illustrated in the right panels of Figure 1. The total X-ray luminosities are much larger for this case, reaching values of up to $9 \times 10^{35}$ ergs s$^{-1}$ at $t = 23,000$ yr, but the stellar wind + interaction regions account for only $10^{34}$ ergs s$^{-1}$ of this emission.

These simulated X-ray luminosities may be compared with the values obtained from the Chandra maps of the regions around HD 5980 by Nazé et al. (2002), who derive $L_X = 1.4 \times 10^{35}$ ergs s$^{-1}$ in the 0.3–10 keV band. This luminosity lies within the range of values for the luminosity of the entire region (SNR + stellar wind + interaction regions; Table 1, col. [5]) obtained from our simulations for an SN explosion with $E_0$ in the $(1-5) \times 10^{50}$ ergs range. For $E_0 \geq 5 \times 10^{50}$ ergs, the predicted X-ray luminosities are too large compared with the observations. Note that for such an energetic SN, the relative contribution to the X-ray luminosity is completely dominated by the SNR, with a negligible contribution from the stellar wind and from the wind/SNR interaction region.

We now turn to the morphology of the region and, as mentioned above, the angle between the symmetry axis ($x$-axis) and the plane of sky has a significant effect on the shape of the X-ray-emitting region. We have already discussed the morphology for the case in which the observer is located along the $x$-axis. In Figure 6, we compare the spatial distribution of the X-ray emission arising in the density distribution computed for model A at 37,000 yr and for model E at 23,000 yr but viewed at three different angles. At 80°, the morphology is very similar to that illustrated in Figures 4 and 5, but the central rings are displaced to one side of the star’s location. At 45°, the displacement is significantly more noticeable, and in the case of model E, only a segment of the bright ring...
formed by the interaction between the stellar wind and the SNR is apparent. At 60°, the morphology is intermediate between the other two angles for which the X-ray emission is illustrated.

Naze et al. (2002) describe the morphology of the X-ray emission as having a size of 130 /C14 × 100°, i.e., 37 × 29 pc and containing a few bright or dark arcs with no obvious limb brightening. One of the arcs that appears to be centered on the star is rather diffuse and clumpy and has an approximate diameter of 60°, corresponding to a physical size of ~5 × 10^{19} cm. In Figure 7, we reproduce the X-ray image of HD 5980 presented by Naze et al. (2002, their Fig. 8) and compare it with the results of model A (top panel; \( t = 37,000 \) yr) and model E (middle panel; \( t = 23,000 \) yr), both of which are calculated under the assumption of an 80° angle between the symmetry axis and the plane of the sky. The crosses in the simulations indicate the location of the star, which is clearly visible as the dark dot in the Chandra image (bottom panel). The size of the extended emission is closer to that given by model A than that of model E. If we assume that the outermost regions of the extended emission can be associated with the SNR rim, then this region is also more similar to model A than to model E, which has too bright a rim. However, the contrast between the internal ring in model A and the background X-ray emission is much greater than the observed contrast. In this respect, the observations are more similar to model E. Furthermore, there is obviously much more structure in the observations as predicted by model E rather than model A. Hence, the extended emission associated with HD 5980 presents a morphology that may be described as intermediate between the morphologies predicted by models A and E, consistent with the result that the observed X-ray luminosities lies between the ones predicted from models A and E. A feature that is not predicted by the simulations is the protrusion at the top left of the X-ray image. Clearly, the simulations are based on idealized assumptions concerning the symmetry and homogeneity of both the SNR and the stellar wind and its windblown bubble. In reality, each of these components is likely to be clumpy and may depart significantly from spherical symmetry and could possibly give rise to the more complex structures observed in the Chandra image.
4. DISCUSSION

In this paper, we describe the interaction of an SNR with the wind of a nearby massive star. This interaction leads to localized sources of X-ray emission embedded in the diffuse emission of the SNR. The emission arising in the SNR/stellar wind interaction is a substantial fraction of the total X-ray luminosity several thousand years after the SNR-stellar wind interaction has initiated. The X-ray luminosity depends primarily on the energy of the supernova event. The simulations are consistent with the general features recently observed in the extended X-ray emission surrounding the WR/LBV binary system HD 5980, supporting the possibility that this extended X-ray emission includes contributions from the interaction between the SNR and HD 5980’s wind. Assuming this scenario, the initial energy of the SN was \((1-5) \times 10^{50}\) ergs, and the SN event occurred between 23,000 and 37,000 yr ago. In support of this scenario, the radial velocities of ISM features that have been observed in the UV and FUV wavelength regions at \(v_{\text{hel}} \approx 300 \text{ km s}^{-1}\) (or \(v \approx 150 \text{ km s}^{-1}\), with respect to the stationary SMC ISM) are consistent with the velocity of the shock front that is expanding into the stellar wind of HD 5980 that is predicted by the simulations. However, before concluding that the 300 km s\(^{-1}\) heliocentric component observed in the spectrum of HD 5980 indeed comes from the wind/SNR interaction region, detailed predictions of the absorption line profiles using gasdynamic models are required.

The simulations predict the presence of X-ray–bright rings. The observations indicate the presence of arcs rather than rings. The rings appear as a consequence of the assumed symmetry in the stellar wind and in the SNR. Clearly, a more detailed model for HD 5980 should contemplate the possibility of a more irregular structure. In particular, HD 5980 consists of two stars with strongly interacting stellar winds that can lead to the formation of large-scale structures. In addition, HD 5980 has undergone a recent LBV-type eruption associated with the star that is currently undergoing a transition from O-type to WR star. In the past, similar enhanced mass-loss episodes are likely to have occurred. Hence, the stellar wind that the SNR is encountering is likely to be structured, with high- and low-density regions. This will lead to additional fluctuations in the density stratification of the interaction region and will definitely produce a more irregular X-ray emission map than the one predicted from our simple model.

The interaction with the SNR ends up destroying the windblown bubble that surrounds the star, leaving only a bow shock separating the SNR and the stellar wind and a small segment of the material that was swept up by the stellar wind on the opposite side of the star. The entire phenomenon, for the cases we have modeled, is very short-lived (\(\sim 10^4\) yr), which, combined with the low frequency of SN events, makes it a very rare phenomenon, not likely to be frequently observed. However, a long-lasting effect is the fact that once the interaction of the SNR with the stellar wind has transpired, any material that had been swept up by the stellar wind is removed and the subsequent propagation of the stellar wind into the ISM proceeds unhindered as it expands into the SNR cavity.

The short-lived phenomenon we describe must occur in all young massive star clusters. We can speculate that if the SN explodes near the center of the cluster, the ejecta will interact with a large number of O-type stars, not just one, as in our simulations. Assuming that each interaction region leads to a luminosity of \((10^35 - 10^37)\) ergs s\(^{-1}\) and that there are 100 nearby O-type stars, a luminosity of \((10^35 - 10^37)\) ergs s\(^{-1}\) is predicted from the whole cluster.

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REFERENCES

Arnaud, M., & Rothenflug, R. 1986, A&AS, 60, 425
Cantó, J., Raga, A. C., & Rodríguez, L. F. 2000, ApJ, 536, 896
de Boer, K. S., & Savage, B. D. 1980, ApJ, 238, 86
Dere, K. P., Landi, E., Young, P. R. & Zanna, G. 2001, ApJS, 134, 331
Fitzpatrick, E. L. & Savage, B. D. 1983, ApJ, 267, 93
Inoue, H., Koyama, K., & Tanaka, Y. 1983, in IAU Symp. 101, Supernova Remnants and Their X-Ray Emission, ed. J. I. Danziger & P. Gorenstein (Dordrecht: Reidel), 535
Hoopes, C. G., Sembach, K. R., Howk, J. C., & Blair, W. P. 2001, ApJ, 558, L35
Koenigsberger, G., Georgiev, L., Peimbert, M., Barbá, R., Niemela, V. S., Morrell, N., Walborn, N. R., Tzvetanov, Z., & Schulte-Ladbeck, R. 2001, AJ, 121, 267
Koenigsberger, G., Georgiev, L., & Georgiev, L. 2002, ApJ, 581, 598
Landini, M., & Monsignori Fossi, B. C. 1991, A&AS, 91, 183
Nazé, Y., Hartwell, J. M., Stevens, I. R., Corcoran, M. F., Chu, Y.-H., Koenigsberger, G., Moffat, A. F. J., & Niemela, V. S. 2002, ApJ, 580, 225
Niemela, V. N. 1988, in Progress and Opportunities in Southern Hemisphere Optical Astronomy, ed. V. M. Blanco & M. M. Phillips (Provo: Brigham Young Univ. Press), 381

Raga, A., Navarro-González, R., & Villagrán-Muniz, M. 2000, Rev. Mexicana Astron. Astrofis., 36, 67
Raga, A. C., Sobral, H., Villagrán-Muniz, M., Navarro-González, R., & Masciadri, E. 2001a, MNRAS, 324, 206
Raga, A. C., Velázquez, P. F., Cantó, J., Masciadri, E., & Rodríguez, L. F. 2001b, ApJ, 559, L33
Shull, J. M., & van Steenberg, M. 1982, Ap&SS, 48, 95
Sobral, H., Villagrán-Muniz, M., Navarro-González, R., & Raga, A. C. 2000, ApPl. Phys. Lett., 77, 3158
Van Leer, B. 1982, ICASE Report 82-30
Velázquez, P. F., de la Fuente, E., Rosado, M., & Raga, A. C. 2001a, A&A, 377, 1144
Velázquez, P. F., Sobral, H., Raga, A. C., Villagrán-Muniz, M., & Navarro-González, R. 2001b, Rev. Mexicana Astron. Astrofis., 37, 87
Ye, T., Turtle, A. J., & Kennicutt, Jr., R. C. 1991, MNRAS, 249, 722
Yusef-Zadeh, F., Law, C., Wardle, M., Wang, Q. D., Fruscioni, A., Lang, C. C., & Cotera, A. 2002, ApJ, 570, 665