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PHOTOIONIZING SHOCKS IN THE ISM

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RESUMEN

Investigamos la estructura de ionización de las regiones H II precursoras que se forman alrededor de los remanentes de supernova (RSN) por medio de cálculos hidrodinámico–radiativos que incluyen un tratamiento detallado de la ionización fuera de equilibrio tanto dentro del RSN como en la región precursora ionizada. Se hace una comparación cualitativa con observaciones del RSN N132D que se ubica en la Nube Mayor de Magallanes.

ABSTRACT

We investigate the ionization structure of precursor H II regions formed around supernova remnants (SNR) by means of radiation–hydrodynamic calculations that include a detailed treatment of the non–equilibrium ionization both within the SNR and in the ionized precursor region. A qualitative comparison is made with observations of the Large Magellanic Cloud SNR N132D.

Key Words: **HYDRODYNAMICS — ISM: H II REGIONS — SHOCK WAVES — SUPERNOVA REMNANTS**

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1. INTRODUCTION

Supernova remnants (SNR) are a source of fast shocks in the interstellar medium (ISM). These shocks heat the ISM gas which then begins to cool radiatively. For postshock gas temperatures between 10^5 and 10^7 K this radiative cooling process produces UV and X–ray photons. The photons diffuse both upstream and downstream: those that travel upstream encounter preshock gas and may produce an extensive precursor H II region, while those that travel downstream influence the ionization and temperature structure of the postshock gas (see e.g., Dopita & Sutherland 1996).

Ionized precursors have been observed around a few SNR. Morse et al. (1996) attributed diffuse emission, brightest in [O III], to a photoionized precursor ahead of the supernova shock in the Large Magellanic Cloud (LMC) remnant N132D. Bohigas, Sauvageot, & Decourchelle (1999) observed decreasing [O III] and [O II] emission with increasing distance (up to 15 pc) from the shock front of the Cygnus Loop SNR, which they conjectured could be a photoionized precursor region. Recently, Ghavamian et al. (2000) have obtained evidence for a photoionized precursor around Tycho's SNR.

The structure of a radiative shock has been described by Dopita & Sutherland (1996). For a constant velocity planar shock an equilibrium shock structure is produced which can be divided into zones that can be thought of in terms of the ionization and cooling history of a parcel of gas as it travels through the shock wave. Not all of these zones are important in young supernova remnants, since the cooling times are much longer than the age of the remnant. Only the ionization zone (where preshock material suddenly finds itself in the hot postshock region and rapidly ionizes towards the collisional equilibrium state), the radiative zone (where the now–ionized gas begins to cool radiatively), and the nonequilibrium cooling zone (where cooling times are shorter than recombination times) need be considered. These zones produce a radiation field that consists of thermal bremsstrahlung, two–photon and free–bound continua as well as resonance lines. This radiation field diffuses both upstream and downstream and can photoionize the region ahead of the shock wave. For the equilibrium shock model the ionized region produced will be the corresponding equilibrium H II region.

However, in the case of a young SNR shock we cannot expect either an equilibrium shock structure or an equilibrium precursor H II region. A *real* SNR shock decelerates with time, hence the SNR postshock region will be a complicated mixture of ionization regions and radiative zones from a continuous range of shock velocities. The hottest gas in the remnant is gas which was shocked early on in the evolution when the shock velocity was highest. This gas has the longest cooling timescale. Gas which has only recently been shocked will have the lowest temperature, hence the highest cooling rate, but will also have had less time to cool. Furthermore, the precursor region will not be an equilibrium H II region because the lifetime of the remnant is much less than the recombination timescale of the precursor gas.

Previous work on the properties of ionized precursor regions has generally assumed that the H II region is in ionization equilibrium. However, a typical recombination timescale is $\sim 10^5/n_e$ yr, where n_e is the electron number density of the gas. In the region of N132D, the density is ~ 3 cm^{-3}, and the estimated remnant age is 3000 yrs, hence any precursor ionized region is likely to be far from ionization equilibrium. Similarly, in the case of the Cygnus Loop, typical ambient densities are ~ 0.1 cm^{-3} and the estimated remnant age is ∼14,000 yrs.

An additional complication is that the remnants of Type II supernovae, such as those that produced the N132D and Cygnus Loop remnants, are likely to be evolving inside of low–density cavities formed by the action of the stellar winds and ionizing photon flux of their progenitor stars. Such remnants will evolve to quite large radii on a short timescale while still in the free expansion stage and will then encounter a dense cavity wall. The interaction with the cavity wall produces a transmitted shock, with lower velocity, that travels into the dense medium. This shock will soon become radiative. There will also be a reflected shock that travels back through the cavity, heating this low density region to very high temperatures ($T > 10^7$ K). The outer shock wave will therefore become radiative before the majority of the remnant has thermalized.

In this paper, we examine the nonequilibrium H II regions formed around supernova remnants. We perform hydrodynamic simulations, which include a treatment of the nonequilibrium ionization state of the gas, the calculation of the emergent ionizing spectrum from the supernova remnant, and the radiative transfer of this ionizing radiation through the precursor region. In particular, we simulate the evolution of a supernova remnant within a low–density cavity–the current scenario for the N132D SNR (Morse et al. 1996)–to make a qualitative comparison with observations of that remnant.

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2. TIME-DEPENDENT EVOLUTION OF A SUPERNOVA REMNANT IN A CAVITY

Observations of the LMC supernova remnant N132D have led Morse et al. (1996) to the conclusion that it is the result of SNR evolution inside a low–density cavity. Comparison of X–ray and optical images of the remnant show that the diffuse optical emission begins just outside the limb–brightened X–ray rim. Analysis of this optical emission as a photoionized region implies an electron density of $n_e \sim 3$ cm^{-3} in this preshock gas. From the X–ray data (Hwang et al. 1993; Morse et al. 1996) the X–ray flux can be fit by an electron density of ~ 15 cm^{-3}, an X–ray shell thickness of 2×10^{18} cm, and a temperature $T_e = 8.4 \times 10^6$ K. This corresponds to a shock of velocity ~ 800 km s^{-1} moving into an ambient medium of density ~ 3 cm^{-3}. The radius of the X–ray remnant is ~ 11 pc and the thickness of the [O III] emitting region is ~ 1 pc. Morse et al. (1996) interpreted the X–ray rim as marking the position of the SNR shock, and the diffuse optical emission as being the photoionized precursor. Assuming a Taylor–Sedov model for the remnant leads to an inferred supernova energy that is too high (10^{52} ergs) if the remnant is assumed to have evolved in a constant density medium with $n_0 = 3$ cm^{-3}, given the implied shock velocity. The conclusion of Morse et al. (1996) is that the remnant has evolved inside a low–density cavity, where $n_0 \sim 0.2$ cm^{-3}. Hughes (1987), on the other hand, postulated that the supernova explosion occurred in a cavity with density ~ 0.01 cm^{-3}.

Accordingly, we perform simulations of supernova remnant expansion in a cavity of radius 10 pc with density 0.3 cm^{-3}, where the surrounding ambient medium has a density of 3 cm^{-3}. The cavity and surrounding medium are initially in pressure balance. The temperature in the ambient medium is 2000 K, which means that the gas is essentially neutral there. The shock velocity upon reaching the cavity rim is $V_s > 1300$ km s^{-1} and the temperature in the swept–up cavity gas is high, $T_e \sim 10^8$ K. This gas emits hard X–rays. This radiation field does not produce much ionization in the surrounding denser ambient medium. When the shock wave hits the cavity wall a slower shock ($V_s \sim 650$ km s^{-1}) is transmitted into the dense ambient medium. The postshock temperature is initially $T_e \sim 10^7$ K, but this shock decelerates as the remnant expands, and by the time the swept up region behind the transmitted shock has a thickness of ~ 1 pc, the shock velocity is below 400 km s^{-1}. The postshock temperature, however, is still $\sim 10^7$ K. The reflected shock that travels back into the cavity reheats the hot gas to temperatures $T_e > 10^8$ K.

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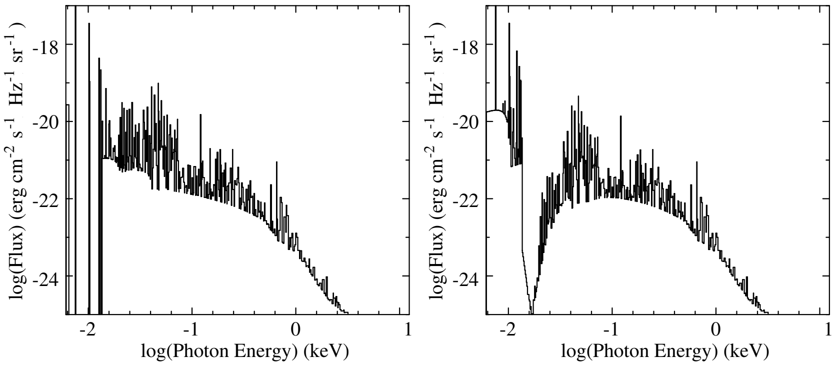

Fig. 1. *Left:* Spectrum emerging from the shock into the precursor region. *Right:* Spectrum intercepted by gas a distance 0.8 pc from the SNR shock

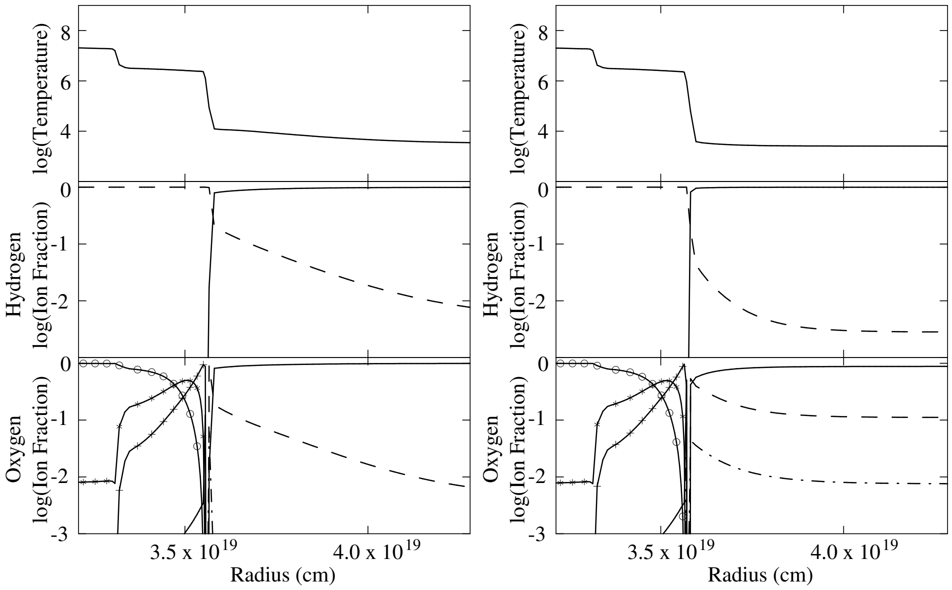

Fig. 2. *Left:* Temperature (top panel) and hydrogen and oxygen ionization fractions (middle and bottom panels) in the immediate postshock and precursor regions. *Right:* Same as left figure but without charge exchange. *Key:* solid line—neutral species; dashed line—singly ionized species; dot–dashed line—doubly ionized species; line with crosses—six times ionized; line with stars—seven times ionized; line with open circles—eight times ionized.

3. RESULTS

The hydrodynamics of the SNR evolution is calculated using a second order Lagrangian Godunov scheme, which captures the details of the interaction of the blast wave with the dense cavity wall and the resultant transmitted and reflected shocks. We calculate the spectrum produced by the postshock gas that emerges into the precursor region taking into account continuum emission (due to thermal bremsstrahlung, two–photon emission, and free–bound emission) and resonance line emission. We use the set of lines with wavelengths less than 2048 Å (i.e., those lines capable of producing ionization) that are listed in the CHIANTI database (Dere et al. 1997). The nonequilibrium ionization state of the gas is calculated using recombination and ionization rates obtained from `http://www.pa.uky.edu/~verner/atom.html`. At this moment Auger ionization is not included. We used abundances appropriate to LMC H II regions, obtained from Russell & Dopita (1990, 1992).

In Figure 1 (left) we plot a typical spectrum that emerges from the shock at a time when the region of swept–up dense material has a thickness of about 1 pc. At this point the transmitted shock has been travelling through the dense gas for some 3,500 yrs and has a velocity of ~ 370 km s^{-1}. We have made no attempt to match this spectrum to the observed *Einstein* flux in the 0.2–4.0 keV band and, in general, the flux in our spectrum is lower, by almost a factor of 10, than that observed. In this simulation, this part of the spectrum is produced by the extremely hot gas in the low–density part of the remnant. This is because the blast wave in the dense medium is not moving fast enough. In Figure 1 (right) we show the spectrum intercepted by gas a distance 0.8 pc from the shock at the same time. We can see from this figure that the softer part of the spectrum is absorbed close to the shock and that only hard X–rays reach gas further out. The low–energy part of the spectrum is produced in the precursor region and is incapable of ionizing the gas.

The effect of the photoionizing radiation on the precursor gas is to produce partial ionization. In Figure 2 we plot the ionization fractions of hydrogen and oxygen in the region immediately pre– and post–shock. In the left hand figure charge exchange is included: the effect is to tie the oxygen ionization state to that of hydrogen. Hydrogen itself is only 10% ionized right next to the shock and this fraction falls off with distance. Oxygen never becomes ionized to O^{++} in the precursor region. The right–hand figure portrays the case when charge exchange is omitted. Although the postshock ionization structure is the same, in the precursor region oxygen manages to achieve a few percent ionization to O^{++}. Thus, charge exchange explains why oxygen is not more ionized in the precursor region (see also Halpern & Grindlay 1980).

In order to obtain a higher degree of ionization in the precursor region more EUV photons are needed. The current spectrum is too hard to completely ionize hydrogen on timescales of the lifetime of the remnant. EUV photons are produced by gas cooling behind radiative shocks whose velocity is only a few hundred km s^{-1}.

4. CONCLUSIONS

The X–ray emitting gas alone is not capable of producing the [O III] observed in the precursor region of the supernova remnant N132D. However, the present simulations assume that the remnant is expanding into essentially neutral gas at 2000 K. We are performing new simulations where the remnant expands into the H II region formed by the progenitor star. In this case, the hydrogen in the ambient medium will be completely ionized and oxygen will be at least singly ionized out to the hydrogen ionization front. Thus, it may be possible that the shock photoionizing spectrum can further ionize oxygen to produce the observed [O III] emission.

Morse et al. (1996) also concluded that the X–ray emitting gas alone is not capable of producing the observed [O III] emission. They invoked the EUV spectrum of shocked dense cloudlets close to the X–ray rim of the remnant as the agent responsable for this emission. Alternative explanations could be the relic H II region itself (unlikely, since the progenitor is thought to be a B0 or later star), or the flash from the supernova. The N132D remnant contains many oxygen rich filaments, which are seen in [O III] and [O II] emission. These filaments do not appear to be emitting X–rays (Morse et al. 1996), however, radiative shocks moving through these O–rich filaments may be an important source of EUV photons.

In these simulations we were unable to reproduce the shock velocity (~ 790 km s^{-1}) required by the X–ray observations. This suggests that the cavity density used was too high and that the density postulated by Hughes (1987) is more realistic. A lower cavity density means a higher shock velocity when the remnant encounters the cavity wall. In the future, we will perform simulations of this scenario.

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