A MODEL OF SNR EVOLUTION FOR AN O-STAR IN A CLOUDY ISM

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Abstract: We present an analytical model of SNR evolution in a cloudy interstellar medium for a single progenitor star of spectral type 05 V. The model begins with the progenitor on the zero-age main sequence, includes the effects of the star's wind and ionizing photons, and ends with the SNR's assimilation by the ISM. We assume that the ISM consists of atomic clouds, molecular clouds, and a hot intercloud phase. The type of SNR that results bears a strong resemblance to N63A in the Large Magellanic Cloud.

Introduction: For many years, it has been desirable to interpret observations of supernova remnants in terms of models of SNR evolution. The Sedov-Taylor model of the 1950s, for example, was the first widely used paradigm. This model assumes the explosion occurs in a medium with a constant or power-law density distribution. Disagreements between the predictions and the observations, particularly when it came to time scales and geometry, led to the realization that satisfactory models of SNR evolution must include more realistic assumptions about the nature of the ambient interstellar medium at the moment of the SN explosion.

Clearly, the state of the ambient ISM at the time of the SN explosion depends not only on its condition at the birth of the SN progenitor star, but also on the effects that this star has on the ISM during the star's lifetime.

This inspired the development of an analytical model of SNR evolution for the case of a single B-star progenitor by Shull, Dyson, Kahn and West [1]. The most interesting prediction of this model is that the SN progenitor should be surrounded at the time of its explosion by a neutral shell of density $n \doteq 10^2$ cm^{-3}. This bubble results from the expansion of hot, ionized gas around the star beyond the star's Strömgren radius. The result is the creation of an SNR with a filamentary, optical shell such as N49 or the Cygnus Loop.

Assumptions: As in the B-star model we assume a three-phase ISM in approximate pressure equilibrium at 10^{-12} dyn cm^{-2} with solar composition [2]. The intercloud medium has a temperature $T \doteq 10^6$ K, and a density $n \doteq 10^{-2}$ cm^{-3}. Atomic clouds have $T \doteq 100$ K, $n \doteq 20$ cm^{-3}, and radii of a few pc, while molecular clouds have $T \doteq 10$ K, $n \doteq 10^3 - 10^6$ cm^{-3}, and radii less than 10 pc. There are about 10 atomic clouds in each spherical volume of radius 10 pc, and the clouds are isothermal, self-gravitating spheres.

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As a rather extreme example, we elected to model a star of spectral type O5 V. Such a star has a mass of about 50 $M_\odot$, radius = 14 $R_\odot$, main-sequence lifetime of 10^6 yr, and an ionizing photon luminosity of 5 x 10^{49} s^{-1}. Additionally, the stellar wind has a terminal velocity of 3000 km s^{-1} and a mass-loss rate of 3 x 10^{-6} $M_\odot$ yr^{-1} [3,4,5].

Pre-SN Evolution on the Main Sequence: The interesting differences between the current model and the model for the B-star are due to the O-star's more intense ionizing flux, energetically important wind, significant mass-loss effects, and shorter main-sequence lifetime. For reasons of brevity, we will present only the predictions of the model, and refer the reader to reference [6] for the details.

The ionizing photon flux will drive an R-type ionization front far into the surrounding medium. In a uniform medium of density n cm^{-3}, its ultimate radius would be 110 $n^{-2/3}$ pc, which would be attained in a timescale of 10^4/n yr.

As the Strömgren sphere is forming, the ionizing flux also evaporates the atomic clouds. Due to their lower temperatures, the molecular clouds will essentially not evaporate [7]. We neglect thermal conduction. Gas is injected into the intercloud medium at the rate of n = 2 x 10^{-6} cm^{-3} yr^{-1}. Clouds must have radii larger than 2 pc to survive until the end of the main-sequence phase. Due to the shortness of the main-sequence lifetime, the gas will not have time to evenly distribute itself, and densities will range from 10^{-2} to 1 cm^{-3}.

This gas will cool to 10^4 K within less than a main-sequence lifetime, have a pressure at most equal to the ambient value, and therefore not flow away from the star to form a neutral shell as it does in our B-star model.

The stellar wind simultaneously plays an important role in this process because, over the star's lifetime, the density of the injected wind's energy, when contained within radii of about 120 or fewer parsecs, is greater than or equal to the pressure of the ambient ISM.

The wind freely expands from the stellar surface out to a radius of approximately 1 pc. This radius is reached in 300 yr. Thereafter, the swept-up intercloud gas, whose density is steadily increasing, controls the wind's dynamics. Because of the low densities involved, this process involves no significant radiative losses. Out to a radius of about 6 pc, the wind radius r is proportional to $t^{3/5}$, where t is the elapsed time. Thereafter, the effect of the increasing density becomes noticeable, and $r \propto t^{2/5}$ until the stagnation radius of 21 pc is reached. At this point, the ram pressure of the wind is counterbalanced by the pressure of the ambient ISM.

Pre-SN Evolution on the Giant Branch: While the star is on the supergiant branch for a time T_{SG} roughly equalling a tenth of its MS lifetime, its ionizing photon flux will become negligible, and the mass-loss rate will increase by a factor of 10.

As the photon flux weakens, recombination of the gas within the Strömgren sphere occurs on timescales of $10^5/n$ yr, which is comparable to T_{SG} for the denser regions beyond 20 pc. Therefore, the pressure drops and the inner and outer boundaries of the sphere respectively move outward and inward. Since this in both cases involves the displacement of denser gas by lower-density gas, Rayleigh-Taylor instabilities may result at both boundaries. The density gradients characterizing these two new boundaries have scale heights of $c_S{*}T_{SG} \doteq 10$ pc.

The increased mass-loss rate enhances the motion of the inner boundary as it moves to seek a new equilibrium position.

The Circumstellar Region at the Time of Explosion: Within 20-30 pc of the star is a volume of ionized, unrecombined wind with $T \doteq 10^6$ K and $n \ll 1$ cm^{-3}. Beyond this, out to a radius of about 100 pc, is a region of neutral, recombined gas at $T \doteq 10^3$ K with n ranging up to 1 cm^{-3}. There are density gradients with scale heights of about 10 pc at both boundaries of this region. Furthermore, molecular clouds will stud both these volumes.

The Explosion and its Aftermath: We assume that the O-star will explode by releasing 10^{51} erg of energy and ejecting about 10 $M_\odot$ of material at speeds of 2×10^4 km s^{-1}.

The ejecta propagate freely throughout the wind zone, the wind's mass being less than 0.2 $M_\odot$. The shock driven into the wind accelerates down the r^{-2} density gradient. The ejecta reach the inner boundary of the recombined region in approximately 10^3 yr.

A jumble of weak transmitted and reflected shocks are generated by the wind shock at the irregular inner boundary. When the ejecta arrive, the main shock driven into the recombined region will have a speed of only 200 $(E_0/10^{51}\ \mathrm{erg})^{1/2}\ (1\ \mathrm{cm}^{-3}/n)^{1/2}$ km s^{-1}. This shock will sweep up 10 $M_\odot$ of material by the time it has penetrated less than 0.1 pc into this region, and thus produce a reverse shock.

Due to the muffling effect of the wind cavity, the transmitted shock wave's adiabatic evolution can be described by a modified Sedov solution in which the epoch t of the shock when it is at radius r is given by $t \propto r^{7/2}\ [1-(r_0/r)^3]^{1/2}$. The latter factor indicates the muffling effect not present in the standard solution.

Whenever the blast wave encounters any remaining atomic or molecular clouds, optically radiative shocks will be driven into them. These clouds will be the only significant sources of optical emission from the SNR.

Comparison of the Model's Predictions to N63A: This model predicts that only hard X-rays and infrared radiation from shocked dust will be emitted while the ejecta traverse the wind zone, but at low intensity. Then, readily detectable X-rays and UV should emanate from the recombination zone, and soft X-rays from the reverse-shocked ejecta.

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Optical emission will originate from any shocked clouds, but there will be no dense, neutral shell, in contrast to the case for a B-star. These events will be followed by the classical snowplow and radiative phases of the Sedov model, but on shortened timescales due to the wind cavity.

The SNR N63A in the LMC strikingly resembles these predictions [8]. This SNR is in a group of O and B stars. Assuming that the progenitor was more massive than the stars remaining in the association, then the progenitor was at least of spectral type O9-O7. The remnant has center-filled X-ray and radio morphologies with radii of about 10 pc. Infrared emission has also been detected by the IRAS satellite. There is no optical shell whatever. The only optical emission comes from two small shocked clouds located between the SN and the Earth.

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