Formation of the outer Rings of SN 1987A

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The nebulosity around SN 1987A has been resolved in increasing clarity by a sequence of images from ground-based telescopes and the Hubble Space Telescope[1−4]. It shows the remarkable triple ring system. A central inner ring is superimposed in projection by two parallel outer rings that are symmetrically displaced along a common axis that joins their three centers and approximately passes through the supernova orthogonally to the three planes and is viewed under 45°[4,5]. The standard interpretation[2,6−10] as an interaction of a blue supergiant wind with the red supergiant wind from a previous evolutionary phase with a higher density in equatorial than in polar direction fails by order of magnitude to explain the narrow width and high density contrast of the observed outer rings[4]. We present a new model for the formation of these outer rings in which the heating of the originally cool red supergiant wind by ionization in the subsequent blue supergiant phase induces hydrodynamic motions that naturally lead to ring formation.

The progenitor star of SN 1987A, Sk-69 202 was a blue supergiant[11] (BSG) with surface temperature $10^{4.2}$K and luminosity $1.3 \times 10^5 L_\odot$ This provides a flux of $S = 10^{46.2}$ ionizing photons/s. This flux ionizes the red supergiant wind from a preceding evolutionary phase and reaches the estimated present distance $r = 10^{18.3}$cm of the outer rings in about 100 yr (standard mass loss rate $\dot{M}_r = 10^{-5} M_\odot$/yr and velocity $v_r = 10$ km/s assumed). On a comparable timescale the BSG wind ($\dot{M}_6 = 10^{-6} M_\odot$/yr and $v_b = 550$km/s) has cleared the innermost 10^{17}cm of the RSG wind whose high density would otherwise have prevented ionization by efficient recombination. These two time spans are short compared to the time scale of evolution described below and will be neglected.

The further evolution of the RSG wind is that of an isothermal gas under acceleration by pressure gradients that result from the original density gradients by heating. With pressure $P = V_s^2 \varrho$ (V_s isothermal sound velocity) and density falling radially off proportional to $1/r^2$ one finds acceleration times $t_{acc} = v/(dv/dt) = \frac{1}{2}(v/V_s^2)r$, proportional to the distance r. Inner regions thus are accelerated faster and move into the still slower outer regions forming a shock front which propagates outward with time. Because of the constancy of the sound speed V_s and the invariance of the hydrodynamic equations and boundary conditions with respect to scale transformations that leave $\xi = r/(V_s t)$ invariant the problem is solved by a similarity solution.

We first consider the spherically symmetric case. The solution then has the form

$$v = V_s\, u(\xi)\ , \quad \varrho = \frac{1}{r^2}\, \bar{\rho}(\xi)$$

and solves the standard hydrodynamic equations[12,13] of conservation of mass and radial motion together with boundary conditions $v \to v_r$, $r^2 \varrho \to \dot{M}/4\pi v_r$ at $r \to \infty$ and $v = 0$ at $r = 0$. There is a unique solution for each value of the parameter v_r/V_s. Figure 1 shows the solution for $T = 11000$K and $v_r = 10$km/s. The (isothermal) shock at $\xi = 3.2$ separates a "supersonic" branch that asymptotically approaches the undisturbed wind from a "subsonic" branch filling the inner region. This shock pattern propagates radially outward with speed $\xi \dot{V}_s = 37.9$km/s and reaches the distance of the outer rings after 15000 yr. The velocity of the shocked gas is $v = 29.4$km/s outwards. This must be compared to spectroscopically inferred velocities of up to 25km/s[5]. The steep density peak behind the shock reaches

$$n_{sh} = 60 \, \frac{\dot{M}_{-5}}{v_6 (r_{18})^2_{sh}} \mathrm{cm}^{-3}$$

where $\dot{M}_{-5}$ is the RSG wind mass loss rate in $10^{-5} M_\odot/\mathrm{yr}$, v_6 its velocity in 10km/s and r_{18} the distance in 10^{18}cm. This remarkable structure has developed from internal dynamics of the ionized RSG wind and is not caused by a piston pushing from inside.

This thin and dense shell would still not suffice to explain the observed ring structure. If however the RSG wind had higher density in equatorial than in polar direction a lateral pressure gradient arises on ionization and pushes gas poleward. In a similar way as in the case of radial gradiants the motion can non-linearly steepen up to high density peaks at intermediate angles ϑ. Again there is a unique similarity solution for each given density profile $\varrho = f(\vartheta)/r^2$ in the undisturbed wind. Density and the radial and lateral velocities become functions of ξ and ϑ,

$$\varrho = \frac{1}{r^2} \, \bar{\varrho}(\xi, \vartheta) \, , \quad v_r = V_s \, u(\xi, \vartheta) \, , \quad v_\vartheta = V_s \, w(\xi, \vartheta)$$

and the time dependent equations of motion and continuity[12,13] reduce to partial differential equations in ξ and ϑ alone. Figure 2 gives such a solution. It shows how at a given radius the density builds up in time to the expected ring shaped peak, here at opening angle $\vartheta \approx 40°$. (This angle depends on the position of maximum curvature in the original density distribution for $t = 0$). The solution was obtained be developing it in inverse powers of ξ up to 3rd order. The solution also incorporates a variation of the undisturbed wind velocity faster by a factor 2 at the pole than at the equator. The original density contrast of 4 leads to the steep and high peak of density

$$n_p = 800 \, \frac{\dot{M}_{-5}}{r_{18}^2 v_6} \, \mathrm{cm}^{-3}$$

which yields $n_p = 250\mathrm{cm}^{-3}$ at the distance of the outer rings. With an estimated depth Δr of $r/20$ the radial column density becomes high enough to shield the gas completely from the ionizing radiation. This happens above a critical density n_c of $\left[S/(4\pi r^2 \Delta r \alpha)\right]^{1/2}$ or

$$n_c = 300 \, \left(\frac{S_{46.2}}{r_{18}^3} \frac{r}{20\Delta r} \right)^{1/2} \, \mathrm{cm}^{-3}$$

where the recombination coefficient to all states except the ground state $\alpha = 10^{-12.6}\mathrm{cm}^3/\mathrm{s}$ [14] was used. Thus the gas in the ring will recombine and cool on a time scale $t_c = 1/(\alpha n_p) =$ 500yr. This is short enough compared to the time that matter remains within the high density region, estimated as of order of several thousand years. This fulfills another requirement[4] namely that the rings were not ionized before the SN occurred: Part of the ring system was not visible when the SN light had not yet reached it.

This model frees the outer rings from their connection to the interior interaction region of the red and blue supergiant winds. We note that now the blue supergiant wind blows into a highly structured red wind relic. This may allow room to interpret the weak extended emission interior to the outer rings[4]. Finally it should be pointed out that planetary nebulae might develop much the same structure under ionization by their smaller but significantly hotter central stars.

We have shown that internal dynamics of the red supergiant wind on ionization and heating in the subsequent blue supergiant phase naturally forms slender rings of high density neutral gas. This gas was reionized by the burst of 10^{57} ionizing photons from the SN explosion and now shows its delicate structure in recombination light.

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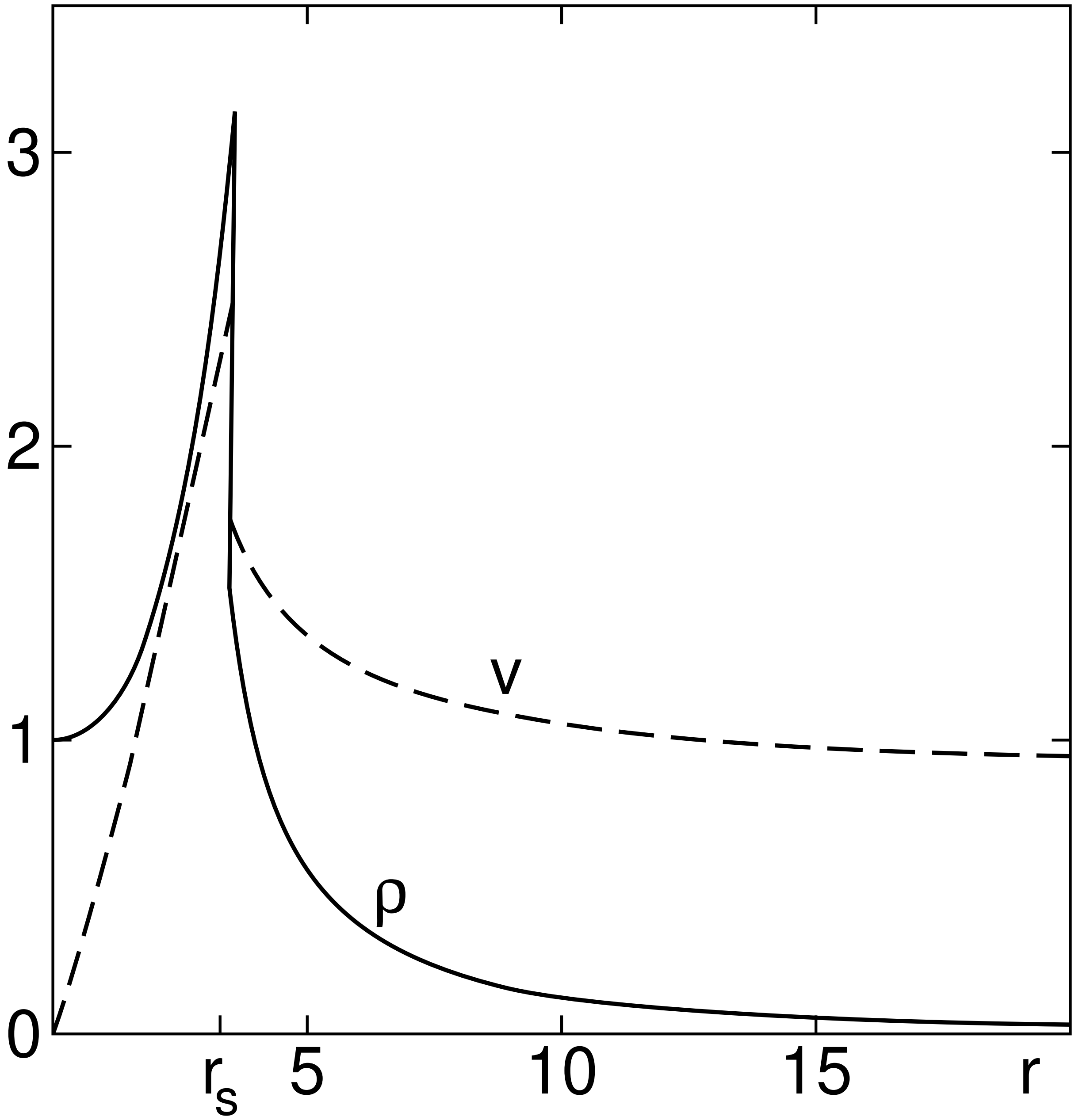

Fig.1 Radial distribution of density ϱ and radial velocity v in a spherically symmetric red supergiant wind ionized at time $t = 0$ and kept at constant temperature (around 10^4K) by the ionizing photon flux of the subsequent blue supergiant stage of the central star. Radial distance r and velocity v are in units of $r_0 = V_s t$ and V_s respectively (V_s isothermal sound velocity). The peak particle density is $60\dot{M}_{-5}/v_6 \mathrm{cm}^{-3}$ at $v_{sh} = 10^{18}$cm and scales proportional to $1/r_0^2$. ($\dot{M}_{-5}$ and v_6 mass loss rate and undisturbed flow velocity in $10^{-5} M_\odot$/yr and 10km/s, respectively. This shell of high density moves outward with time as $r_{sh} = 3.2 V_s t$.

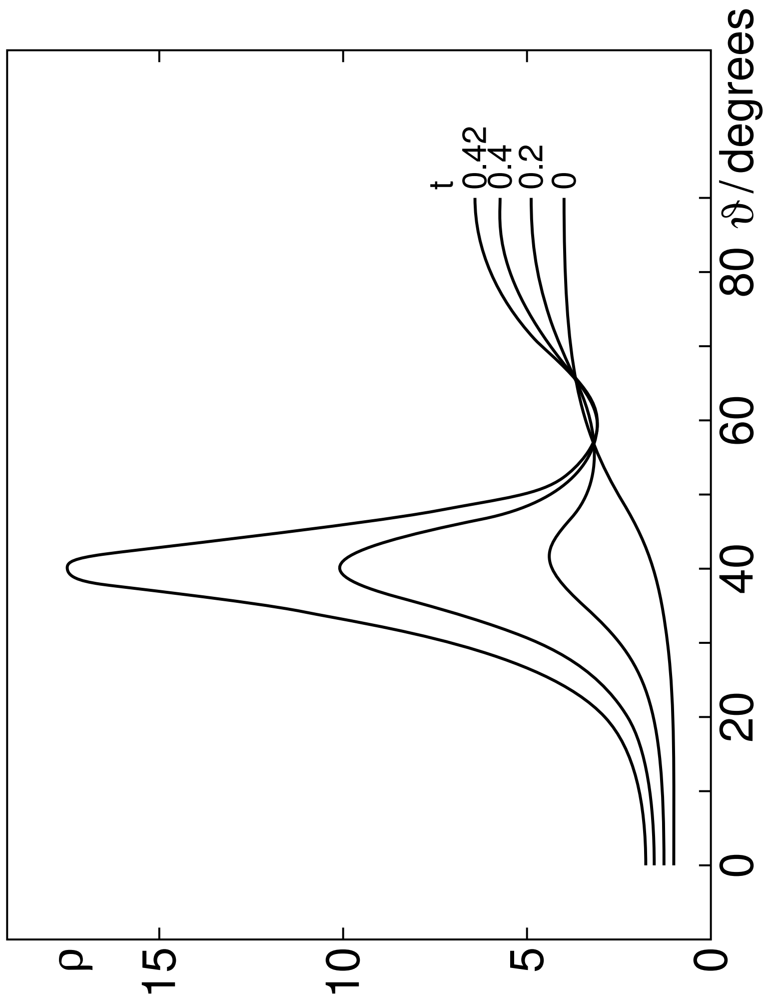

Fig.2 Formation of a ring of high density in the red supergiant wind after ionization and heating. The original distribution (time $t = 0$) has 4 times higher density at the equator than at the pole. The lateral pressure gradients sweep matter up at declination $\vartheta = 40°$ (the position depends on the maximum curvature of the original distribution). Singularity is prevented by shock formation (not shown) behind which the density decreases again inwards similar to Fig.1. This ring pattern of high density and narrow extent propagates with $2.5V_s$ along the conical surface $\vartheta = \vartheta_{\rm max} = 40°$. Units of time and particle density are r/V_s and $44\dot{M}_{-5}/v_6 r_{18}^2)\mathrm{cm}^{-3}$, respectively with r_{18} radius in units of 10^{18}cm. This solution also incorporates a declination dependent undisturbed radial wind velocity with $v_r(\vartheta = 90°) = 1/2 v_r(v = 0)$. There are corresponding solutions for any initial density and radial velocity distribution over ϑ.