The Structure of the Circumstellar Envelope of SN 1987A

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Abstract. The volume around the SN 1987A contains a variety of structures, not just the three rings glowing in recombination lines. Many of these are revealed by light echoes, so are mapped in three dimensions by our optical imaging of the SN environs. The rings reside in a bipolar nebula containing them at its waist and crowns, and which is itself contained in a larger, diffuse nebula with a detectable equatorial overdensity. This diffuse nebula terminates in a denser wall which likely marks the inner edge of a bubble blown by the progenitor’s main sequence wind. Along with mapping these structures, we measure spectroscopically the velocity of the gas, revealing, for instance, kinematic ages for the inner and outer rings in close agreement with each other. The presence of these structures, their ages and morphologies must be included in models explaining the evolution of the progenitor star and its mass loss envelope.

1. Introduction

The nebula around SN 1987A is complex: not only the three rings now seen easily via recombination radiation, but further structure seen in other ways, and inferred from the already interacting SN ejecta. The presence of material of the inner ring was discovered with IUE as narrow emission lines (Fransson et al. 1989), and shown to be spatially resolved from the ground (Wampler & Richichi 1989). The outer rings (the northern “NOR” and southern “SOR”) and the approximate shape of the inner, equatorial ring (“ER”) were found by Crotts et al. (1989). The ring structure was further resolved using the NTT (Wampler et al. 1990) and HST (Jakobsen et al. 1991, Burrows et al. 1995). The kinematics of the ER indicate a true ring, and not a limb-brightened spheroid (Crotts & Heathcote 1991). The rings are connected by a double-lobed nebula with the ER at its waist and likely terminating at its outer extremes at the ORs (Crotts et al. 1995). A light echo just outside the rings (Bond et al. 1991), encompasses a diffuse medium of echoing material (Crotts and Kunkel 1991). This diffuse medium includes an equatorial overdensity in the same plane as the
ER (Crotts et al. 1995). Here we present further, unpublished results bearing on the progenitor star’s nature and the production of this circumstellar nebula.

2. Kinematics of the Three Rings

The velocity field in $\text{[N II]} \lambda 6583$ emission shows a gradient across the ER minor axis like that of a ring, inclined at 43°, expanding radially at $v_{\text{exp}} = 10.3 \text{ km s}^{-1}$ (Crotts & Heathcote 1991). Other groups find 10.3, 8.3 and 11 km s$^{-1}$ (Cumming 1994, Meaburn et al. 1995, Panagia et al. 1996, respectively), confirmed (10.5±0.3 km s$^{-1}$) with $HST$ STIS spectroscopy (Crotts & Heathcote 2000).

More novel is combining the angular resolution of $HST$ and spectral resolution of CTIO 4m echelle spectra ($\sim 8 \text{ km s}^{-1}$ FWHM) to separate ER and OR signals (Crotts & Heathcote 2000). By chance, OR segments more than 1 arcsec from the SN have velocities close to the ER’s, while those near the ER differ from it by up to 30 km s$^{-1}$. Echelle spectra or $\sim 100 \text{ km s}^{-1}$-resolution STIS data together dissect both regimes of the nebula. For signals distinct from the ER, spatial position indicates whether they arise from the SOR or NOR. We find NOR velocities, relative to the 289 km s$^{-1}$ of the SN, of +1 to +24 km s$^{-1}$, and +3 to −23 km s$^{-1}$ for the SOR. The NOR is geometrically similar to the ER, while the SOR is rounder but ovoid. For the SOR we use an inclination alternatively the same as the NOR’s or that which makes it nearly round when de-projected, 43° and 31°, respectively. The kinematic ages implied by these velocities, assuming homologous expansion, are 21700y for the NOR, and 19900y or 20800y for the SOR. A similar ratio for the ER yields 19500y (Crotts & Heathcote 1991), consistent with the ORs (with the 1σ errors of $\approx 1500y$). Full interpretation of these results await successful modeling of pre-SN progenitor evolution, but these ages run counter to statements concerning $HST$ FOS spectra (Panagia et al. 1996) that the NOR is nitrogen-poor versus the ER, and that this underabundance results from the ORs being ejected $\sim 10^4y$ before the ER.

3. Echoing Circumstellar Matter Beyond the Rings

Echo mapping producing three-dimensional maps (Crotts et al. 1995), applied to the region just outside the rings, reveal four features: 1) an oval of 9-15 arcsec radius (depending on observation epoch), modeled by Chevalier and Emmering (1989) as a contact discontinuity (CD) between the red supergiant (RSG) wind and the surrounding bubble blown by the main-sequence (MS) progenitor wind. 2) a sheet of material along the equatorial plane defined by the ER and bisecting the bipolar nebula (c.f. Crotts et al. 1995, Fig. 21); 3) a diffuse echo (Crotts & Kunkel 1991) extending from the bipolar nebula outward to feature #1, and 4) “Napoleon’s Hat,” (Wampler et al. 1990) apparently a discontinuity in the gradient of feature #3. We followed these since 1988-9 until their disappearance, and highlight feature #1 here. Now we are pursuing these features to fainter surface brightness using improved image subtraction e.g. Crotts & Tomaney (1996).

This diffuse medium indicates the duration of RSG mass loss. If the velocities seen at the inner edge of this wind e.g. at the ER, NOR and SOR apply throughout, $v_{\text{exp}} \approx 20 \text{ km s}^{-1}$, the age of this diffuse structure is then $\gtrsim 2 \times 10^5y$. 

Circumstellar Structure of SN1987A

Figure 1. An 85-arcsec wide residual image showing, at increasing radii, echoes from the diffuse circumstellar nebula, contact discontinuity and interstellar medium (130 pc from the SN). With permanent nebulosity and stellar flux removed (but some stellar residuals remaining), the echoes become more visible. Contained within the diffuse echo are the bipolar nebula and rings. This image was obtained on day 750 at the LCO 2.5-meter by W. Kunkel, in a band centered at 6023 Å.

The CD echo lies in fragmented ovals and faded drastically in 1991-2. We centroid on individual echo patches in \((x, y)\) and calculate line-of-sight depth \(z = \frac{x^2 + y^2}{2ct} - ct/2\), where \(t\) is time since maximum light. Figure 2 shows two views of the CD (and the bipolar nebula near the origin) as seen from vantage points perpendicular to the sightline to Earth.

If the “CD” is a true contact discontinuity (Chevalier & Emminger 1989) between the RSG wind and the bubble blown by the MS blue supergiant progenitor, the pressure in this bubble should be nearly uniform over a few parsecs, with the shape of the CD due primarily to ram pressure \(\rho v^2\) against nearly uniform bubble pressure. If the CD is aspherical, this is due to anisotropic \(\rho v^2\). Given the equatorial overdensity (feature # 2 above) in the RSG wind, a polar bulge or even a spherical CD indicates a RSG velocity at the poles higher than at the equator. This wind configuration has not been considered in interacting wind models e.g. Blondin & Lundqvist (1993), Martin & Arnett (1995), Blondin et al. (1996). The presence of the CD and the diffuse material inside it runs counter to some, more complicated geometries proposed for the circumstellar environment of SN 1987A (c.f. Podsiadlowski et al. 1991); indeed we know of no model that successfully incorporates it and the three rings.

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References

Blondin, J.M. & Lundqvist, P. 1993, ApJ, 405, 337
Figure 2. The 3-D locus of the contact discontinuity, bipolar nebula and volume probed by light echoes. Left: the view from far to the north ($x$ is distance in right ascension). The CD wraps around the SN at radius $\sim 4$ pc. Points sampled must lie within the light-echo parabolae for the epochs of observation. Right: view of the CD and bipolar echo seen from far to the east ($y$ is distance in declination). The thick dashed line extending from the northern end of the bipolar nebula to the CD at the same $y$ as the SN denotes Napoleon’s Hat. The diagonal, thin dashed line is the symmetry axis of the bipolar nebula.

Blondin, J.M., Lundqvist, P. & Chevalier, R.A. 1996, ApJ, 472, 257
Bond, H.E., Gilmozzi, R., Meakes, M.G. & Panagia, N. 1990, ApJ, 354, L49
Burrows, C., et al. 1995, ApJ, 452, 680
Chevalier, R.A. & Emmering, R.T. 1989, ApJ, 342, L75
Crotts, A.P.S. & Heathcote, S.R. 1991, Nature, 350, 683
Crotts, A.P.S. & Heathcote, S.R. 2000, ApJ, in press
Crotts, A.P.S. & Kunkel, W.E. 1991, ApJ, 366, L73
Crotts, A.P.S., Kunkel, W.E. & Heathcote, S.R. 1995, ApJ, 438, 724
Crotts, A.P.S., Kunkel, W.E. & McCarthy, P.J. 1989, ApJ, 347, L61
Crotts, A.P.S. & Tomaney, A.B. 1996, ApJ, 473, L87
Cumming, R.J. 1994, Ph.D. thesis (Imperial College)
Fransson, C., et al. 1989, ApJ, 336, 429
Jakobsen, P., et al. 1991, ApJ, 369, L63
Martin, C. & Arnett, D. 1995, ApJ, 447, 378
Meaburn, J., Bryce, M. & Holloway, A.J. 1995, A&A, 299, L1
Panagia, N., et al. 1996, ApJ, 459, 17
Podsiadlowski, Ph., Fabian, A.C. & Stevens, I.R. 1991, Nature, 354, 43
Wampler, E.J. & Richichi, A. 1989, A&A, 217, 31
Wampler, E.J., et al. 1990, ApJ, 362, L13