Observing Supernova 1987A with the Refurbished Hubble Space Telescope

Kevin France, *et al.*
Science **329**, 1624 (2010);
DOI: 10.1126/science.1192134

been detected so far. It is possible that a fraction of the large grains in this region might have been destroyed by a supernova that is thought to have reshaped the region about 1 million years ago (*21*). There are not many cases of local cores with detectable coreshine close to the Galactic plane (Fig. 3). It is not presently clear whether this is due to the increased number of background stars confusing the coreshine signal or to physical effects that cause changes in the dust opacities with Galactic position (*22*).

To investigate the influence of the anisotropic illumination on the coreshine appearance with varying Galactic position, we performed three-dimensional (3D) radiative transfer calculations (*23*) for a 10–solar-mass core (Fig. 4). We used a radial density power-law profile in the outer parts (index –1.8) and a flattening toward the center, in agreement with core density profile estimates (*3*). Two different cases were considered, either with a flattening in the innermost 4000 astronomical units [(AU) 1 AU = $1.496\ 10^{11}$ m], or with a more centrally concentrated density profile, flattening only in the innermost 1000 AU. The coreshine flux in the core with a large flattening varies little with Galactic core position. However, our model shows a slight increase in flux in the direction toward the Galactic center in the four cases where the core is viewed at 90° from the Galactic center line of sight. More prominently, the case with a more concentrated density profile reproduces the central flux depression that is seen in a few dense cores such as L183 and L1544, where the optical depth at 3.6 μm becomes too large for scattered photons to escape. In the investigated sample, only a handful of cores show this inner flux depression. The asymmetrical flux increase for the four cores that are 90° from the Galactic center line of sight is also more pronounced than in the flatter-profile cases. In both types of profile, for the central image where the core is placed in front of the Galactic center, the photons are scattered in the forward direction but have to cross the core, so that the flux is smaller than for the side-illumination cases. In general, the coreshine effect is therefore only weakly dependent on the location of the source in the Galaxy and is dominated by the properties of the core.

The coreshine effect thus provides a direct tool to investigate the grain and ice-mantle growth process, in which turbulence and density are major ingredients (*9*). Because the growth process is continuous, it can serve as a measure of the age of cores, contrary to chemical "clocks," which may suffer from repetitive resets (*1*). A "grain-growth clock" may help distinguish between the currently proposed models (*1*) of how prestellar cores are stabilized before they collapse.

In the optically thin case, the coreshine flux has the potential to independently provide a measurement of the dust column density. Because scattering is highly sensitive to grain size (*15*), the coreshine effect will help improve our understanding of the grain infrared opacities. Moreover, the combined consideration of scattering, extinction, and emission modeling will constrain the detailed 3D structure of cold molecular clouds down to the cores.

The growth of grains has an impact on the ion-neutral cold chemistry within the core via electronic equilibrium and possibly surface reactions, whereas circumstellar disks might be affected by a seed population already containing large particles, as revealed by the coreshine effect. More generally, the grains unveiled by coreshine might help to characterize the recent history of an entire region, as in the case of the Gum Nebula complex, where an absence of coreshine implies the recent destruction of big dust grains, possibly by a supernova explosion.

References and Notes

1. E. A. Bergin, M. Tafalla, *Annu. Rev. Astron. Astrophys.* **45**, 339 (2007).
2. C. F. McKee, E. C. Ostriker, *Annu. Rev. Astron. Astrophys.* **45**, 565 (2007).
3. A. Bacmann *et al.*, *Astron. Astrophys.* **361**, 555 (2000).
4. P. André, S. Basu, S. Inutsuka, in *Structure Formation in Astrophysics*, G. Chabrier, Ed. (Cambridge Univ. Press, Cambridge, 2009), pp. 254–287.
5. A. Stutz *et al.*, *Astrophys. J.* **707**, 137 (2009).
6. L. Hartmann, *Accretion Processes in Star Formation* (Cambridge Univ. Press, Cambridge, ed. 2, 2009).
7. J. Bouwman *et al.*, *Astrophys. J.* **683**, 479 (2008).
8. V. Ossenkopf, *Astron. Astrophys.* **280**, 617 (1993).
9. C. W. Ormel, D. Paszun, C. Dominik, A. G. G. M. Tielens, *Astron. Astrophys.* **502**, 845 (2009).
10. C. Kiss, P. Ábrahám, R. J. Laureijs, A. Moór, S. M. Birkmann, *Mon. Not. R. Astron. Soc.* **373**, 1213 (2006).
11. M. Ridderstad, M. Juvela, K. Lehtinen, D. Lemke, T. Liljeström, *Astron. Astrophys.* **451**, 961 (2006).
12. N. L. Chapman, L. G. Mundy, S.-P. Lai, N. J. Evans, *Astrophys. J.* **690**, 496 (2009).
13. M. McClure, *Astrophys. J.* **693**, L81 (2009).
14. G. G. Fazio *et al.*, *Astrophys. J. Suppl. Ser.* **154**, 10 (2004).
15. J. Steinacker, L. Pagani, A. Bacmann, S. Guieu, L. A. Bacmann, S. Guieu, *Astron. Astrophys.* **511**, A9 (2010).
16. J. S. Mathis, W. Rumpl, K. H. Nordsieck, *Astrophys. J.* **217**, 425 (1977).
17. J. B. Foster, A. A. Goodman, *Astrophys. J. Lett.* **636**, L105 (2006).
18. F. F. S. van der Tak, P. Caselli, C. Ceccarelli, *Astron. Astrophys.* **439**, 195 (2005).
19. A. G. G. M. Tielens, *Annu. Rev. Astron. Astrophys.* **46**, 289 (2008).
20. K. Tachihara, A. Mizuno, Y. Fukui, *Astrophys. J.* **528**, 817 (2000).
21. R. J. Reynolds, *Astrophys. J.* **206**, 679 (1976).
22. G. Zasowski *et al.*, *Astrophys. J.* **707**, 510 (2009).
23. J. Steinacker, A. Bacmann, T. Henning, R. Klessen, M. Stickel, *Astron. Astrophys.* **434**, 167 (2005).
24. http://lambda.gsfc.nasa.gov/product/cobe/dirbe_overview.cfm.
25. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. J.S. is grateful for the hospitality and financial support of the Observatoire de Paris and LERMA, where some of this work was performed. We also thank two anonymous reviewers.

3 June 2010; accepted 16 August 2010
10.1126/science.1193211

Observing Supernova 1987A with the Refurbished Hubble Space Telescope

Kevin France,[1] Richard McCray,[2] Kevin Heng,[3,4]* Robert P. Kirshner,[5] Peter Challis,[5] Patrice Bouchet,[6] Arlin Crotts,[7] Eli Dwek,[8] Claes Fransson,[9] Peter M. Garnavich,[10] Josefin Larsson,[9] Stephen S. Lawrence,[11] Peter Lundqvist,[9] Nino Panagia,[12,13,14] Chun S. J. Pun,[15] Nathan Smith,[16] Jesper Sollerman,[9] George Sonneborn,[8] John T. Stocke,[1] Lifan Wang,[17] J. Craig Wheeler[18]

Observations with the Hubble Space Telescope (HST), conducted since 1990, now offer an unprecedented glimpse into fast astrophysical shocks in the young remnant of supernova 1987A. Comparing observations taken in 2010 with the use of the refurbished instruments on HST with data taken in 2004, just before the Space Telescope Imaging Spectrograph failed, we find that the Lyα and Hα lines from shock emission continue to brighten, whereas their maximum velocities continue to decrease. We observe broad, blueshifted Lyα, which we attribute to resonant scattering of photons emitted from hot spots on the equatorial ring. We also detect N v λλ1239, 1243 angstrom line emission, but only to the red of Lyα. The profiles of the N v lines differ markedly from that of Hα, suggesting that the N^{4+} ions are scattered and accelerated by turbulent electromagnetic fields that isotropize the ions in the collisionless shock.

The death of a massive star produces a violent explosion known as a supernova (SN), which expels matter at hypersonic velocities. Supernovae deposit large amounts of mechanical energy and nucleosynthesized elements into the surrounding interstellar medium, driving the physical and chemical evolution of galaxies. The shock impact of the SN debris with ambient matter creates a radiating system known as a supernova remnant. SN 1987A (first observed on 23 February 1987), the brightest such event observed since Kepler's supernova (SN 1604) (*1*), provides a unique opportunity to witness the development of a supernova remnant (*2*, *3*). Because SN 1987A is only 50 kpc away in the Large Magellanic Cloud, the Hubble Space Telescope's (HST's) superb angular resolution is sufficient to resolve the interaction of its shocks with circumstellar material. To track and interpret the temporal, spatial, and spectral evolution of SN1987A, we present observations obtained on 31 January 2010 with the recently repaired Space Telescope Imaging Spectrograph (STIS) and compare them with the results from the last epoch of observations (18 to 23 July 2004) (*4*), before the instrument's failure in August 2004.

The rapidly expanding debris of a SN explosion interacts hydrodynamically with circumstellar matter. If the circumstellar matter has a smooth density distribution, a double-shock structure will be established (*5*). A forward shock (blast wave) propagates into the circumstellar matter, creating a layer of hot, shocked gas. The pressure of this layer drives a reverse shock (RS) into the SN debris. This double-shock structure propagates outward until the blast wave encounters a relatively dense obstacle. In the case of SN 1987A, encountering the equatorial ring drives a reflected shock backward into the debris that merges it with the RS.

The equatorial ring is a relatively dense (atomic hydrogen densities of $n_H \sim 10^3$ to 10^4 atoms cm^{-3}) structure of diameter 1.34 light years (ly), inclined at an angle $i = 45°$ with respect to the line of sight (*6*–*8*). This ring is attributed to a mass-loss event that occurred ~20,000 years before the SN explosion (*9*, *10*). The first evidence of interaction of the blast wave with the ring appeared in 1995, when a rapidly brightening optical "hot spot" appeared in images taken with the Wide Field Planetary Camera 2 aboard the HST (*11*, *12*). Today, the ring is encircled by ~30 hot spots (Fig. 1). Movie S1 shows the emergence of these hot spots and the expansion of the debris from 1994 to 2006. The location of these emission spots just inside the ring and their long duration suggests that they result from shocks that propagate into dense fingers that protrude inward from the equatorial ring (*13*).

Radiation from the RS can be observed at optical and ultraviolet wavelengths. Before it reaches the RS, the outer layer of the SN debris consists mostly of partially ionized hydrogen and helium gas that has been expanding freely since the explosion. When neutral hydrogen atoms cross the RS, they are excited and ionized by collisions with ions in the shocked plasma. If the atoms are excited before they are ionized, they will produce Lyα (1216 Å) and Hα (6563 Å) line emission. On average, about 1 Lyα photon and 0.2 Hα photons are produced for every hydrogen atom crossing the RS (*14*–*16*).

The emission properties of the RS in SN 1987A are similar to those of the Balmer-dominated shock emission observed in several supernova remnants, where photons are produced via collisional excitation (and charge exchange) rather than recombination (*14*, *17*, *18*). In other collisionless supernova remnants, the blast wave overtakes nearly stationary circumstellar matter, whereas in SN 1987A, fast-moving hydrogen gas in the SN debris overtakes the RS. As the hydrogen atoms in the SN debris cross the RS, they freely stream with radial velocity $v_r = r/t_e$, where r is the radius of the RS measured from the explosion center, and t_e is the time since the explosion. Likewise, the atoms have Doppler velocity (projected along the line of sight) $v_z = -r\cos\theta/t_e$, where θ is the angle between the streaming SN debris and the line of sight to the observer. When they are excited by collisions with the shocked gas, the neutral hydrogen atoms are not deflected, so the Doppler shifts of the resulting emission lines that we observe (Fig. 1) correspond to the projected ballistic velocity of the unshocked SN debris.

The unique mapping between distance along the line-of-sight and Doppler shift allows us to

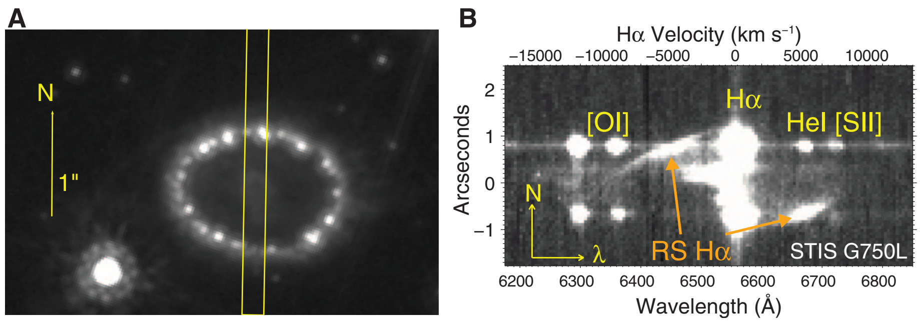

Fig. 1. (**A**) HST-Advanced Camera for Surveys image obtained on 28 November 2003 in the F625W filter with an exposure time of 800 s, illustrating the slit orientation used in our experiment. N, north. (**B**) STIS G750L spectrum of SN 1987A obtained on 31 January 2010, centered on the Hα emission line. The vertical bar at the center of the image is stationary Hα emission from interstellar or circumstellar gas. The bright spots at the north and south of this bar are the emissions from Hα + [N II] λλ6548, 6583 Å from hot spots on the equatorial ring. [O I] λλ6300, 6364, He i λ 6678, and [S II] λλ6716, 6731 Å emission from the hot spots is also observed. The blueshifted streaks near the center are Hα emission excited by radioactivity in the interior of the SN debris. The curved, blueshifted streak extending from the north side of the vertical bar and the redshifted streak on the south side (denoted with orange arrows) are Hα emission from the brightest parts of the RS.

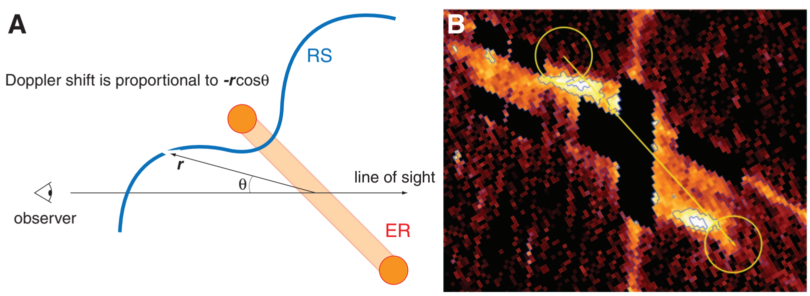

Fig. 2. (**A**) Schematic illustration of the location of the RS with respect to the equatorial ring (ER), which is inclined 45° to the line of sight. (**B**) Hα emission from the RS transformed into a cross-sectional view through the circumstellar ring (see text). The diameter of the equatorial ring is 1.34 ly. The top and bottom yellow circles represent the near (north) and far (south) sides of the equatorial plane of the ring, respectively. The circles represent the cross section of the ring, and contours highlight the emission peaks on the northern and southern streaks.

[1]Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309–0389, USA. [2]JILA, University of Colorado, Boulder, CO 80309–0440, USA. [3]Eidgenössische Technische Hochschule Zürich, Institute for Astronomy, Wolfgang-Pauli-Strasse 27, CH-8093, Zürich, Switzerland. [4]Institute for Advanced Study, School of Natural Sciences, Einstein Drive, Princeton, NJ 08540, USA. [5]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA. [6]Service d'Astrophysique Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Saclay, Orme des Merisiers, FR 91191 Gif-sur-Yvette, France. [7]Department of Astronomy, Mail Code 5240, Columbia University, 550 West 120th Street, New York, NY 10027, USA. [8]NASA Goddard Space Flight Center, Code 665, Greenbelt, MD 20771, USA. [9]Department of Astronomy, Oskar Klein Centre, Stockholm University, 106 91 Stockholm, Sweden. [10]225 Nieuwland Science, University of Notre Dame, Notre Dame, IN 46556–5670, USA. [11]Department of Physics and Astronomy, Hofstra University, Hempstead, NY 11549, USA. [12]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA. [13]Instituto Nazionale di Astrofisica, Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy. [14]Supernova Ltd, OYV #131, Northsound Road, Virgin Gorda, British Virgin Islands. [15]Department of Physics, University of Hong Kong, Pok Fu Lam Road, Hong Kong, China. [16]Department of Astronomy, University of California, Berkeley, CA 94720–3411, USA. [17]Department of Physics and Astronomy, Texas A&M University, College Station, TX 7784–4242, USA. [18]Department of Astronomy, University of Texas, Austin, TX 78712–0259, USA.

*To whom correspondence should be addressed. E-mail: kheng@phys.ethz.ch

convert the spectrum of Fig. 1 into a map of the location of the RS (Fig. 2). The Hα emission is concentrated just inside the equatorial ring, because at these locations, the RS penetrates into denser regions of the SN envelope, where the flow is held back by shocks reflected from the ring. The net Hα flux observed through the 52″ × 0.2″ slit in the total RS (northern blueshifted plus southern redshifted streaks, Fig. 1) is 3.3 (±0.5) × 10^{-13} erg cm^{-2} s^{-1} (*19*). This value is a factor of about 1.7 greater than that measured in July 2004 (*4*) and February 2005 (*20*).

Unlike Hα photons, Lyα photons experience resonant scattering by hydrogen atoms. Thus, Lyα emission is not observed at wavelengths immediately blue- and redward of 1216 Å because of scattering by hydrogen atoms in the Milky Way and Large Magellanic Cloud (Fig. 3). Figure 4 shows comparisons of one-dimensional (1D) scans of Lyα (dark streaks in Fig. 3) and Hα (bright streaks in Fig. 1) emission from the RS. The observed Hα and Lyα fluxes have been increased by factors of ≈ 1.5 and 8, respectively, to correct for interstellar extinction along the line of sight to SN 1987A (*21*, *22*). On the north side of the equatorial ring, the ratio of Lyα to Hα photon fluxes has a fairly constant value near 40 for velocities between –2500 and –6000 km s^{-1} (Fig. 4). This ratio is much greater than the expected photon production ratio of 5:1 for a Balmer-dominated shock (*15*, *16*). Moreover, the Hα emission fades for blueshift velocities < –8000 km s^{-1}, whereas the Lyα emission remains bright for blueshift velocities approaching –12,000 km s^{-1}. If the Lyα photons are produced by the same mechanism as the Hα photons, then the Lyα-to-Hα ratio should be the same for all observed velocities, but it is not. Therefore, most of the observed Lyα emission cannot be produced directly by hydrogen atoms crossing the RS. Unlike Hα, the broad Lyα emission is not confined to a narrow strip delineating the RS surface (Fig. 3).

We propose a different mechanism to account for the highly blueshifted Lyα emission. As the SN blast wave enters the equatorial ring, the shocked hot spots on the ring become bright

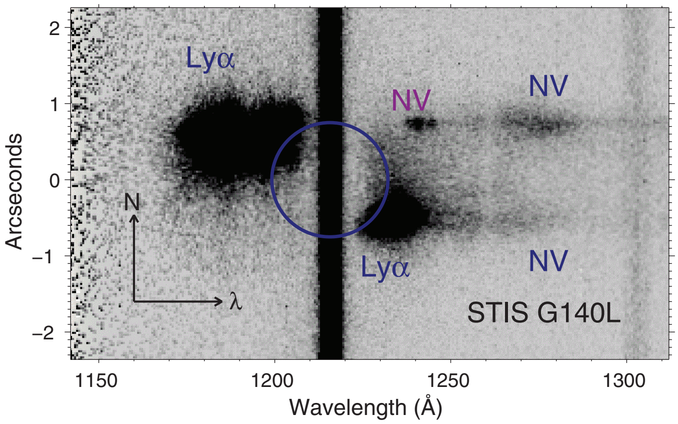

Fig. 3. STIS G140L observations of SN 1987A, acquired on 31 January 2010. The black vertical stripe is the slit image in geocoronal Lyα. The blue circle approximates the location of the circumstellar emission ring. Broad, faint features seen on the north and south sides between about 1260 and 1290 Å (labeled NV in blue) are produced by nitrogen ions in the RS, and the shock-excited N v hot-spot emission is labeled in magenta.

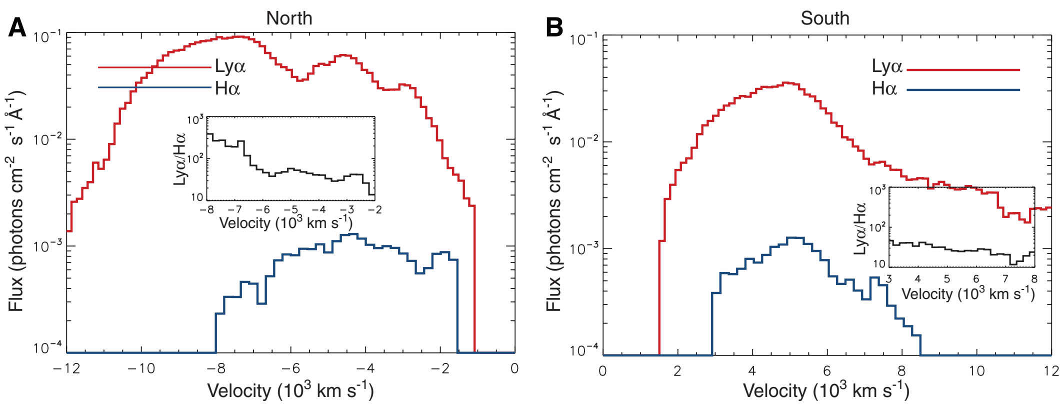

Fig. 4. (**A**) Integrated Hα and Lyα emission from the RS on the north side of the equatorial ring. Although the Hα emission approaches zero blueward of –8000 km s^{-1}, it has been artificially truncated in this plot because of strong contamination from [O I] λλ6300, 6364 Å present in the hot spot (Fig. 1). (Inset) Ratio of Lyα to Hα. The broad dip in the Lyα emission near –6000 km s^{-1} may be due to absorption by interstellar Si ii (λλ1190, 1193 Å). Interstellar absorptions from Si ii (λλ1190, 1193 Å; λλ1260, 1265 Å; and λλ1526,1533 Å) are clearly detected on the sightline to a nearby star. (**B**) Velocity profiles for the southern, redshifted emission. We truncate the southern Hα profile at $v \geq 8500$ km s^{-1} because the Hα flux at these velocities is consistent with a combination of detector background and [S II] emission scattered inside of the equatorial-ring radius.

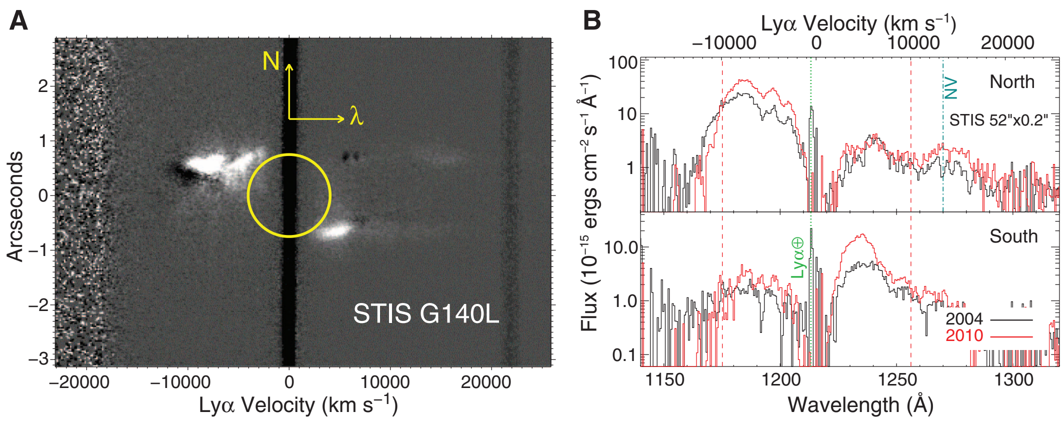

Fig. 5. (**A**) Lyα 2010 to 2004 difference image, scaled such that gray indicates similar intensities in the two epochs. The yellow circle approximates the location of the circumstellar emission ring. (**B**) 1D spectra of the Lyα emission from the north and south regions (*27*). The narrow feature labeled "⊕" is residual emission from Earth's upper atmosphere.

sources of Lyα radiation. This radiation is invisible to observers on Earth because it is centered at zero velocity with respect to the interstellar neutral hydrogen, and its linewidth is narrow ($\Delta v < 300$ km s^{-1}) (*8*, *13*) so that it is entirely blocked by the interstellar medium. Roughly half of this radiation propagates inward into the SN debris, where the Lyα photons may be resonantly scattered by hydrogen atoms that are expanding with radial velocities ranging from 3000 to 9000 km s^{-1}. In the rest frame of the hydrogen atoms in the expanding debris, photons propagating inward are blueshifted. If they are then scattered backward toward Earth, they will be blueshifted a second time. There is no corresponding bright, high-velocity, redshifted Lyα component on the south side of the equatorial ring (Figs. 3 and 4). The Lyα photons that are emitted radially inward by the ring hot spots on the south side are seen as blueshifted by hydrogen atoms in the onrushing debris. Unlike the case in the north, photons from the south that are scattered toward the observer receive a redshift that cancels out this blueshift. This leaves the Lyα photons at approximately zero velocity, where they will be scattered or absorbed before reaching us.

To check the plausibility of such a mechanism, it is necessary to verify that a sufficient number of Lyα photons are emitted by the hot spots to account for the observed high-velocity Lyα and that the neutral hydrogen layer in the expanding SN envelope has sufficient optical depth to scatter Lyα photons by roughly half of the observed maximum velocity (i.e., 6000 km s^{-1}). It is not possible to measure the emitted Lyα flux from the hot spots directly because this radiation is blocked by interstellar hydrogen atoms. We can estimate the strength of Lyα emission using the direct Hα emission from the ring, applying a theoretical scaling [Lyα:Hα ~ 5 to 10; (*23*)]. The Hα hot-spot emission within the STIS slit in the 2010 observations (≈2.1×10^{-12} erg cm^{-2} s^{-1}) suggests that the hot-spot Lyα flux in 2010 is ~3 to 7 photons cm^{-2} s^{-1}. This is sufficient to account for the broad blueshifted Lyα emission (Fig. 4).

Regarding the question of optical depth in the line wings of Lyα, the radial column density of hydrogen atoms in the debris is roughly $N_H \approx M_H/(4\pi R^2 m_H)$, where $M_H \sim 5M_\odot$ (here, $M_\odot$ is the mass of the Sun) is the estimated mass of hydrogen in the SN envelope, $R \approx 6 \times 10^{17}$ cm is the radius of the envelope, and m_H is the mass of the hydrogen atom. For these estimated values, $N_H \approx 1.3 \times 10^{21}$ cm^{-2}. The optical depth of such a column to Lyα photons, Doppler shifted by $v_{1000} = v/(1000$ km s$^{-1})$ (where v is the velocity), is given roughly by $\tau \approx N_H\sigma_o\{(\gamma/4\pi^2)/[\Delta f^2 + (\gamma/4\pi)^2]\}$ (*24*), where the frequency shift is $\Delta f/f_0 = v/c$ (here, c is the speed of light), σ_o is the line-center absorption cross section, and $\gamma = 6.3 \times 10^8$ s^{-1} is the spontaneous decay rate of electrons in the excited state of the hydrogen atom leading to the emission of Lyα photons. For $v_{1000} = -6$, $\tau \approx 0.1$; for comparison, $\tau > 2.5$ for $|v_{1000}| < 1$. Our estimate of the available Lyα photon budget from the hot spots provides an ample margin for this mechanism to operate, even if <50% of the hot-spot Lyα enters the debris. A measurable fraction of the Lyα photons emitted by a hot spot that enter the SN debris will be backscattered and emerge with blueshifts ranging up to ~ –12,000 km s^{-1}.

The Lyα emission brightened from 2004 to 2010 (Fig. 5). We observed two primary features: (i) The Lyα emission has increased in brightness by factors of 1.6 to 2.4 for the north and south shock emission, and (ii) the maximum Doppler shift in the northern blueshifted Lyα emission is decreasing as a function of time. We also note the faint glow seen on the north and south sides at wavelengths ranging from about 1260 to 1290 Å, also visible in Fig. 3. This emission cannot be attributed to Lyα, because it would require the Lyα emission on the north side to be redshifted by velocities up to +20,000 km/s, whereas the actual Lyα emission on that side is blueshifted (Fig. 3).

We propose that this emission comes from fast-moving N^{4+} ions in a thin layer immediately downstream from the RS. Neutral or singly ionized nitrogen atoms that cross the RS and enter the shocked plasma are repeatedly ionized by collisions in the shock transition zone. As it passes through the Li-like ionization stage (N^{4+}), a nitrogen atom may be excited to the 2^2P fine-structure state and emit a N v 1239 or 1243 Å photon, or it may be ionized to N^{5+}. The number of N v photons produced per nitrogen atom passing through the RS will be equal to the ratio of the N^{4+} 2^2P excitation rate to its ionization rate. The Lyα excitation rate is approximately equal to the ionization rate; however, the excitation rate producing the N v emission (which is dominated by collisions with protons and alpha particles) exceeds the ionization rate by a factor of several hundred (*25*, *26*). We estimate that each nitrogen atom that passes through the RS will emit ~600 N v photons before it becomes fully ionized. Given the enriched abundance of nitrogen (N/H ~ 2×10^{-4}) (*7*) in the equatorial ring (and presumably in the outer debris of SN 1987A), the identification of these emissions as N v is plausible.

The putative N v emission is redshifted on the northern side of the RS, because the nitrogen atoms are ionized and accelerated by the turbulent electromagnetic fields in the isotropization zone of the collisionless shock before they emit N v photons. This is in contrast to the hydrogen atoms, which are not deflected notably from free expansion when they emit Lyα. If our identification of this faint feature as N v is correct, we are seeing redshifts on the north side extending to ~12,000 km s^{-1}. The profile of the N v emission will be a convolution of the projected velocity distribution function of the N^{4+} ions with the shock surface, both of which are unknown. But it is probable that the line profile will also have a blueshifted wing extending to at least ~ –12,000 km s^{-1}. We cannot discern this wing because it will be buried under the much brighter Lyα emission. A critical test of our hypothesis will be the observation of the profile of the C iv λλ1548, 1550 Å doublet, which we estimate to have a brightness ~0.3 times that of N v λλ1239, 1243 Å. The C iv doublet should have the same intrinsic emission profile as N v, but it will not be confused with Lyα emission and absorption.

References and Notes

1. D. Arnett, J. N. Bahcall, R. P. Kirshner, S. E. Woosley, *Annu. Rev. Astron. Astrophys.* **27**, 629 (1989).
2. R. McCray, *Annu. Rev. Astron. Astrophys.* **31**, 175 (1993).
3. R. McCray, *AIPC* **937**, 3 (2007).
4. K. Heng *et al.*, *Astrophys. J.* **644**, 959 (2006).
5. R. A. Chevalier, *Astrophys. J.* **258**, 790 (1982).
6. N. Panagia, R. Gilmozzi, F. Macchetto, H.-M. Adorf, R. P. Kirshner, *Astrophys. J.* **380**, L23 (1991).
7. P. Lundqvist, C. Fransson, *Astrophys. J.* **464**, 924 (1996).
8. P. Gröningsson *et al.*, *Astron. Astrophys.* **479**, 761 (2008).
9. A. P. Crotts, S. R. Heathcote, *Nature* **350**, 683 (1991).
10. T. Morris, P. Podsiadlowski, *Science* **315**, 1103 (2007).
11. P. Garnavich, R. P. Kirshner, P. Challis, *IAU Circ. 6710* (1997).
12. S. S. Lawrence *et al.*, *Astrophys. J.* **537**, L123 (2000).
13. C. S. J. Pun *et al.*, *Astrophys. J.* **572**, 906 (2002).
14. R. A. Chevalier, R. P. Kirshner, J. C. Raymond, *Astrophys. J.* **235**, 186 (1980).
15. E. Michael *et al.*, *Astrophys. J.* **593**, 809 (2003).
16. K. Heng, R. McCray, *Astrophys. J.* **654**, 923 (2007).
17. R. A. Chevalier, J. C. Raymond, *Astrophys. J.* **225**, L27 (1978).
18. K. Heng, *Publ. Astron. Soc. Aust.* **27**, 23 (2010).
19. We used the STIS G140L (the spectral resolution $\Delta\lambda$ = 1.2 Å) and G750L ($\Delta\lambda$ = 9.8 Å) modes, with the 52″ × 0.2″ slit, to observe SN 1987A on 31 January 2010 for total exposure times of 8612 and 14200 s, over 6 and 10 exposures, respectively.
20. N. Smith *et al.*, *Astrophys. J. Lett.* **635**, L41 (2005).
21. N. B. Suntzeff, P. Bouchet, *Astron. J.* **99**, 650 (1990).
22. S. Scuderi, N. Panagia, R. Gilmozzi, P. M. Challis, R. P. Kirshner, *Astrophys. J.* **465**, 956 (1996).
23. D. E. Osterbrock, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Univ. Science Books, Mill Valley, CA, 1989).
24. G. B. Rybicki, A. P. Lightman, *Radiative Processes in Astrophysics* (Wiley-Interscience, New York, 1979).
25. J. M. Laming, J. C. Raymond, B. M. McLaughlin, W. P. Blair, *Astrophys. J.* **472**, 267 (1996).
26. K. J. Borkowski, J. M. Blondin, R. McCray, *Astrophys. J. Lett.* **476**, L31 (1997).
27. If one attributes the faint redshifted features to N v λλ1239,1243 Å, one should subtract 6150 km s^{-1} (the Lyα minus N v velocity difference) from the Lyα velocity scale to measure the corresponding Doppler shift.

28. K.F. thanks M. Beasley for enjoyable discussions. Support for this research was provided by NASA through grant GO-11181 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, under NASA contract NAS5-26555.

Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1192134/DC1
Movie S1

11 May 2010; accepted 20 August 2010
Published online 2 September 2010;
10.1126/science.1192134
Include this information when citing this paper.