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THE REVERSE SHOCK OF SNR 1987A AT 18 YEARS AFTER OUTBURST[1]

Nathan Smith,[2,3] Svetozar A. Zhekov,[4,5] Kevin Heng,[4] Richard McCray,[4] Jon A. Morse,[6,7] and Mike Gladders[8]

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ABSTRACT

We use low-dispersion spectra obtained at the Magellan Observatory to study the broad Hα emission from the reverse shock of the infant supernova remnant SNR 1987A. These spectra demonstrate that the spatiokinematic structure of the reverse shock can be distinguished from that of the circumstellar ring and hot spots, even at ground-based spatial resolution. We measure a total dereddened Hα flux of $1.99(\pm0.22) \times 10^{-13}$ ergs s^{-1} cm^{-2} at an epoch 18.00 yr after outburst. At 50 kpc, the total reverse shock luminosity in Hα is roughly 15 $L_\odot$, which implies a total flux of neutral hydrogen atoms across the reverse shock of 8.9×10^{46} s^{-1}, or roughly 2.3×10^{-3} $M_\odot$ yr^{-1}. This represents an increase by a factor of ~4 since 1997. Lyman continuum radiation from gas shocked by the forward blast wave can ionize neutral hydrogen atoms in the supernova debris before they reach the reverse shock. If the inward flux of ionizing photons exceeds the flux of hydrogen atoms approaching the reverse shock, this preionization will shut off the broad Lyα and Hα emission. The observed X-ray emission of SNR 1987A implies that the ratio of ionizing flux to hydrogen atom flux across the reverse shock is presently at least 0.04. The X-ray emission is increasing much faster than the flux of atoms, and if these trends continue, we estimate that the broad Lyα and Hα emission will vanish in $\lesssim$7 yr.

Subject headings: circumstellar matter — shock waves — supernovae: individual (SN 1987A) — supernova remnants

Online material: color figure

1. INTRODUCTION

The collision between the ejecta of SN 1987A and its circumstellar ring is now in full bloom, signaling the birth of the supernova remnant SNR 1987A. This interaction was predicted (Luo & McCray 1991; Luo et al. 1994; Chevalier & Dwarkadas 1995; Borkowski et al. 1997) shortly after the discovery of the circumstellar ring. It began about a decade after the outburst, with the discovery of the first of many "hot spots" (Sonneborn et al. 1998; Michael et al. 2000; Pun et al. 2002). These hot spots are thought to result when the forward blast wave encounters and transmits radiative shocks into dense protrusions, or "fingers," pointing to the interior of the ring. Since then, hot spots have encircled the entire ring (Sugerman et al. 2002).

Behind the blast wave, the expanding supernova debris are decelerated by a reverse shock (e.g., Chevalier 1982). This nonradiative shock is seen as very broad, high-velocity Lyα and Hα emission features in Space Telescope Imaging Spectrograph (STIS) data (Michael et al. 2003, 1998; Sonneborn et al. 1998). This emission, which was predicted by Borkowski et al. (1997), results from the collisional excitation of neutral H atoms from the supernova debris crossing the shock front. Using a series of long-slit STIS spectra, Michael et al. (1998) mapped the geometry of the reverse shock, finding it to reside within roughly ±30° of the equator. New ground-based observations reported here, supplemented by additional observations with STIS (Sonneborn et al. 1998; K. Heng et al. 2005, in preparation), show that the broad Lyα and Hα reverse shock emission has increased by a factor ~4 since 1997. Meanwhile, the X-ray emission from SNR 1987A has brightened at a rapidly accelerating rate (Park et al. 2005). The blast wave interaction with the hot spots now dominates the X-ray emission (Zhekov et al. 2005).

In this Letter we present new spectra from the Magellan Observatory that demonstrate that we can continue to study the emission from this reverse shock with ground-based telescopes, despite the recent demise of STIS. We also discuss the possibility that the shocked gas will produce sufficient ionizing luminosity to photoionize hydrogen atoms in the supernova debris before they reach the reverse shock, and thereby suppress the broad Lyα and Hα emission.

2. MAGELLAN OBSERVATIONS

We observed SN 1987A during the commissioning run of the Low Dispersion Survey Spectrograph 3 (LDSS-3) mounted on the Clay Telescope of the Magellan Observatory on the evening of 2005 February 24 (February 25 UT), almost exactly 18 yr after the supernova was first discovered. LDSS-3 has an STA0500A 4064 × 4064 CCD detector. At red wavelengths it has a pixel scale of 0ʺ.189 × 1.124 Å and an effective spectral resolution of ~5 Å ($R = 1300$), with a 0ʺ.8 (~4.5 pixel) slit width. During the observations, the weather was clear and the seeing was ~0ʺ.8. The slit aperture was centered on the supernova and oriented at P.A. $= -10°$, aligned with the minor axis of the equatorial ring. Wavelengths and velocities were measured with respect to the rest wavelengths of the narrow nebular emission along the slit. Airglow lines and emission from the surrounding H II region were subtracted by fitting the emission from the background sky along the slit.

The region of the long-slit spectrum around Hα resulting

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[1] Based on observations made at the Clay Telescope of the Magellan Observatory, a joint facility of the Carnegie Observatories, Harvard University, the Massachusetts Institute of Technology, the University of Arizona, and the University of Michigan.

[2] Center for Astrophysics and Space Astronomy, University of Colorado, 389 UCB, Boulder, CO 80309; nathans@casa.colorado.edu.

[3] Hubble Fellow.

[4] Joint Institute for Laboratory Astrophysics, University of Colorado, 440 UCB, Boulder, CO 80309.

[5] On leave from the Space Research Institute, Sofia, Bulgaria.

[6] Department of Physics and Astronomy, Arizona State University, P.O. Box 871504, Tempe, AZ 85287-1504.

[7] Current address: Observational Cosmology Laboratory, Mail Code 665, Goddard Space Flight Center, Greenbelt, MD 20771.

[8] Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101.

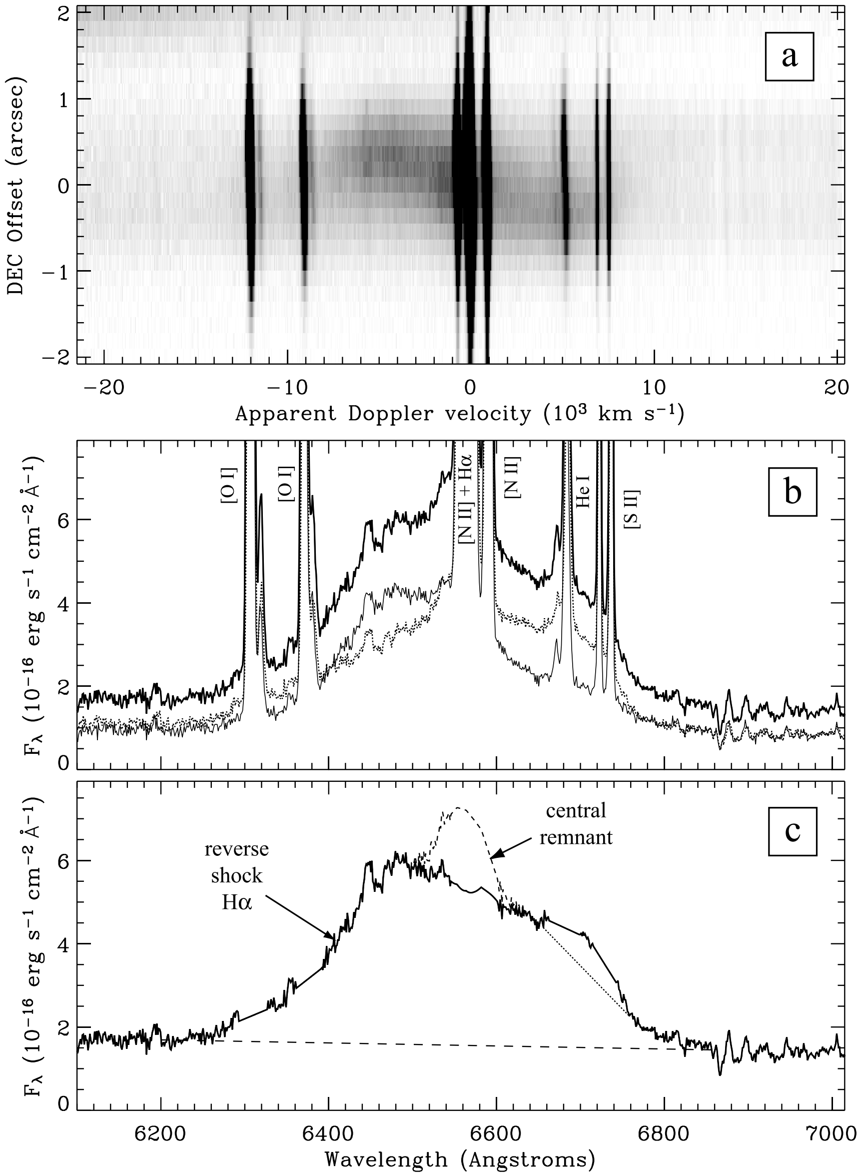

FIG. 1.—LDSS-3 spectra of SN 1987A showing the Hα reverse shock emission. (*a*) Long-slit spectrum showing narrow emission lines from the ring and hot spots, as well as very broad ($\pm 10^4$ km s^{-1}) Hα emission from the reverse shock. (*b*) Extracted spectra. The top tracing (*thick black line*) is the total emission integrated over $\pm 1''$ in the top panel, whereas the thin tracing is the blueshifted side of the reverse shock at $0''$–$1''$, and the dotted tracing is the redshifted side of the shock at $-1''$–$0''$. (*c*) Emission from the reverse shock with the narrow emission components removed. The thick black tracing shows the spectrum used to estimate the pure reverse shock emission. The dashed tracing includes the Hα emission from the central remnant, which would increase the estimated flux by +6.5%. The straight line segment shows a conservative approximation for the reverse shock flux interpolated over He I λ6680 and the [S II] doublet, which would be 6% less than the total flux in the solid tracing. The dashed black line shows the continuum level we chose in measuring the total reverse shock flux. [*See the electronic edition of the Journal for a color version of this figure.*]

from a total exposure time of 900 s is shown in Figure 1*a*. In order to flux-calibrate the LDSS-3 spectrum in 2005 February, we interpolated between the flux measured in 2004 December and 2005 May in *Hubble Space Telescope* (*HST*) Advanced Camera for Survey (ACS) images. We used images in the F658N filter, which includes narrow Hα and [N II] emission from the circumstellar ring and hot spots. We extracted the flux over the same spatial region centered on the northern half of the ring in both the images and the LDSS-3 spectrum, and summed the flux over the F658N filter bandpass ($\Delta\lambda \simeq 50$ Å) in the spectrum. Tracings of the resulting flux-calibrated spectrum are shown in Figure 1*b*, where we display the total flux within $\pm 1''$, as well as separate extractions for the northern (blueshifted) and southern (redshifted) sides of the nebula.

In order to isolate the very broad emission from the reverse shock, we interpolated across the narrow nebular emission lines from the ring and hot spots (Fig. 1*c*). We also removed the emission hump due to rapidly fading Hα emission from the central remnant by subtracting a Gaussian profile (had we included this emission, the total flux would have been 6.5% higher). Interpolating across He I λ6680 and the red [S II] doublet was somewhat subjective; we relied on what appeared to be reverse shock emission at ~6700 Å between the two sets of lines. This resulted in a red bump in the reverse shock line profile. This is probably the best representation of the true reverse shock emission, and is used for the estimate below. A very conservative estimate made by interpolating linearly from 6660 to 6760 Å (the dotted line in Fig. 1*c*) would have resulted in a total flux about 6% less than the value we quote below.

We measure a total Hα flux for the broad reverse shock component of 1.37(±0.15) × 10^{-13} ergs s^{-1} cm^{-2} on 2005 February 25. This corresponds to the black tracing in Figure 1*c*, integrated from 6200 to 6860 Å, and is continuum-subtracted using the continuum level shown by the straight dashed line in Figure 1*c*. This estimate includes an adjustment of +15% for those parts of the reverse shock on the east and west edges of the ring that are excluded from the aperture. Finally, adopting $E(B-V) = 0.16$ (Fitzpatrick & Walborn 1990) and $R = 3.1$, we multiply the observed reverse shock flux by a correction factor of 1.453 to estimate a dereddened broad Hα flux of 1.99(±0.22) × 10^{-13} ergs s^{-1} cm^{-2}.

3. MASS FLUX ACROSS THE REVERSE SHOCK

The total dereddened flux we measure at Earth corresponds to a total luminosity in the broad Hα line of about 5.63×10^{34} ergs s^{-1} at a distance of ∼50 kpc, or roughly 15 $L_\odot$. From this we can infer the flux of neutral hydrogen atoms across the reverse shock. For each neutral H atom crossing the reverse shock, roughly 1 Lyα and 0.21 Hα photons will be emitted (Michael et al. 2003). Thus, dividing the intrinsic Hα luminosity by the energy per Hα photon and multiplying by a factor of 5 gives a total luminosity of hydrogen atoms across the reverse shock of $\dot{N}_{\rm H} \simeq 8.9 \times 10^{46}\ {\rm s}^{-1}$, or a total hydrogen mass flux of roughly $2.3 \times 10^{-3}\ M_\odot\ {\rm yr}^{-1}$. Michael et al. (2003) found that the main emitting surface area of the reverse shock was within ±30° of the equator, just inside the nebular ring. To first order, the density of neutral H atoms in the debris prior to crossing the reverse shock is then

$$n_{\rm H} \simeq \frac{\dot{N}_{\rm H} t}{4\pi R_{\rm RS}^3 \tan 30°},$$

where $\dot{N}_{\rm H} = 8.9 \times 10^{46}\ {\rm s}^{-1}$ is the number of hydrogen atoms crossing the reverse shock, $R_{\rm RS}$ is the present radius of the reverse shock, and $t = 18$ yr is the time since outburst. Here we have assumed that the supernova debris are in free expansion, so that $R_{\rm RS} = V_{{\rm H}\alpha} t$. Taking the observed velocity $V_{{\rm H}\alpha} \simeq 10^4\ {\rm km\ s}^{-1}$, we find $R_{\rm RS} \simeq 0.16$ pc. This is roughly 80% of the radius of the forward shock, taken to be the radius of the ring. This ratio is close to the theoretically expected value for self-similar expansion (Chevalier 1982). The Hα flux we measure implies $N_{\rm H} \simeq 60$–$70\ {\rm cm}^{-3}$.

Figure 2 shows the history of $\dot{N}_{\rm H}$ as inferred from STIS observations of broad Hα and Lyα since 1997 (Sonneborn et al. 1998; Michael et al. 1998; K. Heng et al. 2005, in preparation) and the present observation. The estimated error bars of the values derived from the STIS observations are large, mainly because the corrections for narrow emission lines were substantially greater in the lower dispersion STIS spectra. From Figure 2, we see that $\dot{N}_{\rm H}$ has increased by a factor of ∼4 since the first observation of broad Lyα from the reverse shock in 1997 (Sonneborn et al. 1998).

4. WILL PREIONIZATION SHUT OFF THE REVERSE SHOCK EMISSION?

The hot shocked gas lying immediately outside the reverse shock surface is a luminous source of ionizing photons, roughly half of which will propagate inward to photoionize hydrogen atoms in the supernova debris before they reach the reverse shock. If the luminosity of these ionizing photons exceeds that of the hydrogen atoms, the broad Lyα and Hα emission will vanish. Will this event take place, and if so, when?

We can estimate the luminosity of ionizing photons from the forward shock of SNR 1987A from *Chandra* X-ray observations. Spectral analysis of the Low Energy Transmission Grating observations (Zhekov et al. 2005; also S. Zhekov et al. 2005, in preparation) shows that a two-shock model with temperatures of 0.51 and 2.7 keV, respectively, gives an excellent fit to the X-ray spectrum at $t = 17.5$ yr. For such a model, most of the ionizing photons are EUV photons with energies well below the 0.4–10 keV *Chandra* band. From the two-shock model spectrum, we estimate an inward luminosity of ionizing (>13.6 eV) photons of $F_i \simeq 3.7 \times 10^{45}\ {\rm s}^{-1}$, where we have included a factor of 1.4 to account for the brightening of X-rays that took place between $t = 17.5$ and 18.0 yr, and a factor 0.5 to account for the fact that only half of the ionizing photons will propagate inward. It follows, then, that the ratio of ionizing photon luminosity to hydrogen atom luminosity at $t = 18.0$ yr is $R_i = F_i/\dot{N}_{\rm H} \simeq 0.04$.

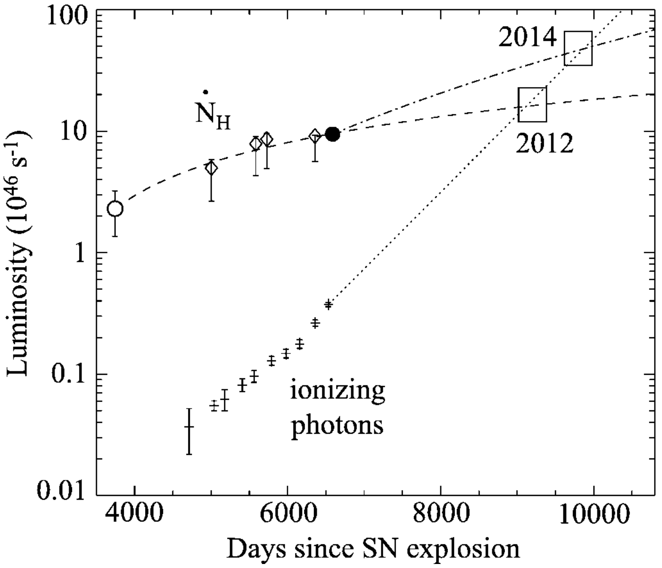

FIG. 2.—Luminosity of H atoms vs. ionizing photons at the reverse shock in SNR 1987A. The X-ray fluxes used to derive the ionizing photon curve are taken from Park et al. (2005) and then converted into photon luminosity using the same two-shock model as explained in the text. The dotted line represents the increase of a factor of 1.7 yr^{-1}, extrapolating from the behavior of the X-ray data over the past few years. The Hα data from this paper (*filled circle*) and from K. Heng et al. (2005, in preparation; *diamonds*), and Lyα data from Sonneborn et al. (1998; *open circle*) are used to calculate the H-atom luminosity (see text). The dashed and dash-dotted lines mark the likely lower limit ($\propto t$) and upper limit ($\propto t^5$) to the future evolution of the H-atom luminosity, respectively.

We regard this estimate as conservative, because we know that the complex system of shocks in SNR 1987A must have velocities ranging from ∼150 km s^{-1} (as observed in the line profiles of the optical hot spots; Pun et al. 2002) to ∼300–1700 km s^{-1} (as observed in the X-ray line profiles; Zhekov et al. 2005). We estimated F_i based on the best model fit to the observed X-ray spectrum, which requires shocks of ∼600 and ∼1400 km s^{-1}, respectively. This may be a significant underestimate, because shocks with velocities in the range $150\ {\rm km\ s}^{-1} \le V_S \le 500\ {\rm km\ s}^{-1}$ might contribute substantially to F_i, but relatively little to the *Chandra* band.

At present, the X-ray luminosity of SNR 1987A is increasing by a factor of ∼1.7 every year (Park et al. 2005), more rapidly than the luminosity of hydrogen atoms across the shock. If present trends continue, as indicated in Figure 2, F_i should overtake $\dot{N}_i$ by about 2012 to 2014. This event could occur 1–2 yr later if the expanding SN ejecta have a high He abundance, because absorption by He atoms could reduce the effective value of F_i. We regard the prediction in Figure 2 as very conservative, however. As we have suggested, we may have underestimated the value of F_i at 18 yr. Moreover, Luo et al. (1994) predicted that once the blast wave envelops the circumstellar ring, the ionizing luminosity should rise very rapidly to a value of $F_i \simeq 2 \times 10^{48}\ \mathrm{s}^{-1}$. This rapid rise, and the consequent vanishing of the reverse shock emission, could happen anytime during the next several years.

Additional uncertainty arises from the extrapolation of $\dot{N}_{\mathrm{H}}$. There are two hydrodynamic scenarios that might bracket its evolution. The first is the self-similar solution describing the expansion of a supernova envelope with density law $\rho(v, t) \propto t^{-3}v^{-n}$ into a uniform circumstellar medium (Chevalier 1982). In this scenario, the radii of the blast wave and the reverse shock both increase as $R \propto t^{(n-3)/n}$, and the mass luminosity increases as $\dot{N}_{\mathrm{H}} \propto t$. We regard this behavior as a probable lower limit to the rate of increase of $\dot{N}_{\mathrm{H}}$. But $\dot{N}_{\mathrm{H}}$ must begin to increase more rapidly in the near future. The blast wave is now overtaking the dense hot spots on the circumstellar ring, and each such encounter will send a reflected shock inward toward the reverse shock. The reflected shocks will eventually merge with the reverse shock and bring it nearly to a halt. Thereafter, $\dot{N}_{\mathrm{H}} \propto t^{(n-4)}$, or $\propto t^5$ for a typical value $n = 9$ (Eastman & Kirshner 1989). We regard this as a probable upper limit to the future evolution of $\dot{N}_{\mathrm{H}}$. These two limiting behaviors of $\dot{N}_{\mathrm{H}}$ are shown as the dashed curves in Figure 2.

5. DISCUSSION

When the suppression of the broad Hα emission is seen, it will provide vital insights into the radiation hydrodynamics of the developing SNR. For example, if the suppression occurs early, as we might expect for reasons noted above, it would provide evidence for substantial ionizing radiation from shocks too slow to contribute substantially to the observed X-ray spectrum. Furthermore, we do not expect the suppression to take place uniformly around the reverse shock. X-ray images (Park et al. 2005) certainly show a substantial amount of structure. Even if the supernova debris have cylindrical symmetry, we would expect the broad Hα and Lyα emission to vanish first near the brighter sources of ionizing radiation (i.e., the bright X-ray knots). With ground-based telescopes, such variation should be evident in the evolution of the line profiles.

Yogi Berra said, “It’s tough to make predictions, especially about the future.” That statement certainly applies to the future evolution of SNR 1987A. Even so, we think that the reverse shock emission is likely to vanish soon enough that it merits continued vigilance with both ground- and space-based telescopes. Yogi Berra also said, “You can observe a lot just by watching.”

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