MAPPING HIGH-VELOCITY Hα AND Lyα EMISSION FROM SUPERNOVA 1987A

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ABSTRACT

We present new Hubble Space Telescope images of high-velocity Hα and Lyα emission in the outer debris of SN 1987 A. The Hα images are dominated by emission from hydrogen atoms crossing the reverse shock (RS). For the first time we observe emission from the RS surface well above and below the equatorial ring (ER), suggesting a bipolar or conical structure perpendicular to the ring plane. Using the Hα imaging, we measure the mass flux of hydrogen atoms crossing the RS front, in the velocity intervals (−7500 < V_{obs} < −2800 km s^{−1}) and (1000 < V_{obs} < 7500 km s^{−1}), M_H = 1.2 × 10^{−3} M_⊙ yr^{−1}. We also present the first Lyα imaging of the whole remnant and new Chandra X-ray observations. Comparing the spatial distribution of the Lyα and X-ray emission, we observe that the majority of the high-velocity Lyα emission originates interior to the ER. The observed Lyα/Hα photon ratio, (R(Lα/Hα)) ≈ 17, is significantly higher than the theoretically predicted ratio of ≈5 for neutral atoms crossing the RS front. We attribute this excess to Lyα emission produced by X-ray heating of the outer debris. The spatial orientation of the Lyα and X-ray emission suggests that X-ray heating of the outer debris is the dominant Lyα production mechanism in SN 1987 A at this phase in its evolution.

Key words: circumstellar matter – shock waves – supernovae: individual (SN 1987A)

1. INTRODUCTION

The reverse shock (RS) in SN 1987 A is the surface where the freely expanding debris is suddenly decelerated as it encounters circumstellar matter. Hydrogen atoms crossing the shock are excited by collisions in the shocked plasma and emit Hα and Lyα photons having Doppler shifts corresponding to the projected velocity of the freely expanding debris immediately inside the shock. This emission was predicted by Borkowski et al. (1997) and subsequently observed and interpreted by Sonneborn et al. (1998) and Michael et al. (1998).

The freely expanding supernova debris obeys a “Hubble’s Law,” i.e., the Doppler velocity is given by V_{obs} = zH, where z is the projected distance along the line of sight measured relative to the center of the explosion and t is the time since the supernova explosion (∼27.5 yr in mid-2014). Thus, surfaces of constant Doppler shift are planar sections of the debris. The fluxes of Hα and Lyα photons emitted at the RS are directly proportional to the fluence of hydrogen atoms across the shock.

These facts create a unique opportunity to map the three-dimensional structure of the RS in SN 1987 A and provide an empirical framework for studies of the shock interaction. This opportunity has been exploited in observations with the Space Telescope Imaging Spectrograph (STIS). In the STIS observations, the Hα emission from the RS was clearly visible near the circumstellar equatorial ring (ER), where the shock is strongest (Michael et al. 1998, 2003; Heng et al. 2006; France et al. 2010). The ring is inclined ≈43°, north being the near side (Panagia et al. 1991; Plait et al. 1995; Sugerman et al. 2005). Michael et al. (2003) modeled the RS surface, concluding that the observed emission was confined to within ∼±30° of the ring plane, similar to the opening angle of the ring observed at radio wavelengths (Ng et al. 2013). However, the STIS exposures were not deep enough to detect Hα emission at high latitudes (i.e., out of the ER plane), where the fluence of atoms is much smaller than near the equator. Moreover, none of the spectroscopic observations included enough STIS slit locations to map the entire shock surface.

In this Letter, we describe the results of an observing campaign to map the high-velocity Hα and Lyα emission using filters that transmit the blue- and redshifted emission from the debris while suppressing the bright emission from the ER. In Sections 2 and 3, the new Hubble Space Telescope (HST) observations are described; for the first time we detect emission from the shock above and below the ring plane. In Section 4, we compare Hα, Lyα, and X-ray observations, arguing that the majority of the Lyα flux is driven by X-ray heating of the outer ejecta, as proposed in our earlier work (e.g., France et al. 2011; Larsson et al. 2011; Fransson et al. 2013).

2. HST OBSERVATIONS AND IMAGE REDUCTION

We obtained images of SN 1987 A with the WFC3 camera in four filters to isolate the high-velocity Hα: blue high-velocity
**Figure 1.** 2014 August 20 STIS G750L spectra with WFC3 filter curves: dashed cyan lines represent F645N and F665N, while the solid red line represents the F656N filter. The F658N filter is shifted about 2 nm to the red of F656N and is not shown here. Narrow emission lines from the ER are labeled in yellow and the broad RS arcs are labeled in orange. The dotted purple line represents the F656N filter bandpass is shown on an inclination of 3° and two narrow-band filters centered on shocked Hα and Hβ, respectively. Emission from the A-b and A-r regions are products of H atoms passing through the RS near the north and south side of the ER, respectively. The bright Hα emission features (A-b and A-r) from the RS have been partially mapped in three dimensions by STIS observations (e.g., Michael et al. 2003; Heng et al. 2006; France et al. 2010).

In the “Hα Blue” image (Figure 2, top) a bright crescent-shaped feature covers the north side of the ER (as defined by the [NII] contours), labeled B-b. Given the 3° inclination of the ring, the B-b region must originate from significantly above the ring plane and it to be visible in this configuration. This image also shows faint streaks that cross the ring extending toward the south (C-b). The features labeled A-r, B-r, and C-r are analogous to the blue side, but reflected about the major axis of the ER. The additional feature labeled D-r is probably emission from the internal debris, which is expanding with radial velocities ranging up to 3500 km s⁻¹ (McCray 1993; Larsson et al. 2013).

Combining the “Hα Blue” and “Hα Red” images, we measure the spatial extent of the high-velocity Hα regions (positional uncertainties <0.05′). The high-velocity material interior to the ring (A regions) has north-south and east-west diameters of 0.94×1.31, which when including the inclination translates to physical dimensions of (9.9×9.8)×10¹⁷ cm (assuming d = 50 kpc). This suggests a symmetric, radial flow with a maximum radial velocity of 5.7×10³ km s⁻¹ (at 27.5 yr since the supernova explosion). The B regions on the blue and red side have maximum angular distances from the center of the remnant of 0.82 and 0.98, respectively. These correspond to maximum deprojected distances and radial velocities of 8.6×10¹⁷ cm and 10.0×10³ km s⁻¹ for the north/blue and 10.4×10¹⁷ cm and 11.9×10³ km s⁻¹ for the south/red. The C region has a maximum observed angular extent of 1.57 from the center of the remnant, corresponding to 14.5×10¹⁷ cm and 16.7×10³ km s⁻¹ assuming free expansion.

3. Morphology of the RS Surface

Fransson et al. (2013) noted that the large observed velocity of the Hα at late times ($V_{\text{obs}} \gtrsim 11 \times 10^3$ km s⁻¹ at $t > 20$ yr) suggests that the RS front has expanded beyond the ring plane. They conclude that the RS extent in the polar direction is 15% larger than the ER radius and 40% larger than the RS radius in the ring plane. We find deprojected velocities of 10–12×10³ km s⁻¹ in the B-b and B-r regions, corresponding to RS radii 40–70% larger than the 6.1×10¹⁷ cm ring radius. The C regions extend to 2–2.5 times the ER radius.

To interpret the high-velocity Hα images, we recall that surfaces of constant Doppler shift are planar sections of the freely expanding supernova debris. Therefore, the pass bands of the “Hα Blue” and “Hα Red” filters map to slabs in physical space, as illustrated in Figure 5. Portions of the RS surface visible through the “Hα Blue” filter (colored blue) reside within the slab delineated by the blue vertical lines, while those visible through the “Hα Red” filter (colored red) reside within the slab delineated by the red vertical lines. The density of the outer debris crossing the RS front, and therefore the mass flux, is $d_{\text{obs}} \propto r^{-3}V^{-9}$ (Luo et al. 1994). The much higher density of the debris crossing the RS in the equatorial direction relative to the polar direction ($\rho_{\text{eq}}/\rho_{\text{pol}} \sim 10^7$) makes the A region much brighter (detectable spectroscopically within 10 yr of the explosion). The lower density material flowing out of the ring plane (B and C regions) is fainter, only now visible with the dedicated high-velocity Hα imaging and sufficient time for the...
polar shock structure to be angularly separated from the ring plane.

While much of the RS surface is not imaged because of the discrete velocity surfaces transmitted through the filters (shaded gray in Figure 5), the emerging picture for the extended Hα emission in the off-plane regions suggests a bipolar morphology. This is expected due to the high pressure of the equatorial plane, owing to the presence of the ring (Blondin et al. 1996). Assuming the outer ejecta pressure is proportional to $r_s V^2$, the C polar region pressure is $\sim 1/1800$ of the equatorial region pressure. This general picture resembles the bipolar surfaces suggested for the pre-supernova interacting wind picture by Blondin & Lundqvist (1993), however, recent studies of a "pre-explosion twin" to the SN 1987 A system (SBW1; Smith et al. 2013) suggest that interacting winds may not be required to explain the nebular morphology.

A second possible explanation for the C region emission is a conical or helical structure (e.g., Smith 2007; Smith et al. 2013) connecting the ER with the extended outer rings (ORs). In this scenario, (1) high-velocity ejecta crossing this structure would be limb-brightened, explaining the bright edges in the C-b and C-r emission, and (2) the southern C-b streaks would be offset to the east compared to the northern C-r streaks by an amount comparable to the E–W offset of the ORs (e.g., Sugerman et al. 2005), which is indeed what is observed in Figure 2. In this picture, the C emission would essentially be a new SN 1987 A intermediate ring system. Deep Hα imaging spectroscopy to map the region could distinguish between these scenarios and may shed light on the progenitor structure, including the possibility of a binary merger prior to the supernova explosion (Morris & Podsiadlowski 2007).

4. HIGH-VELOCITY Lyα IMAGING

Figure 3 illustrates the contribution of different far-UV emission components to the F122M image. Interstellar H I blocks the center of the Lyα line profile over the velocity range $-1500 \text{ km s}^{-1} < V_{\text{obs}} < +1500 \text{ km s}^{-1}$ (France et al. 2011), and so excludes emission from the shocked ring and hotspots, which have Doppler shifts $\Delta V < 300 \text{ km s}^{-1}$ (Pun et al. 2002). Based on the HST-COS spectrum, we estimate that 90–95% of the total emission in the F122M image is contributed by high-velocity Lyα. The remaining 5–10% is mostly NV $\lambda 1240$ Å emission from the ER and high-velocity N$^4+$ ions crossing the RS front.

Separation of the peak Lyα and ER emission is complicated on the bright northern side by the 43° projection on the plane of the sky, however, there is separation between the Lyα and Hα rings profiles in the east–west direction. The east–west ring diameters are 1″44 (±0″05), 1″62 (±0″05), and 1″53 (±0″10) for Lyα, Hα, ER (F656N), and X-ray images, respectively. The Lyα image is slightly offset with respect to the ER, with the largest separation (1.35 × 10$^{17}$ cm) at the western edge.
Figure 3. (Top left) 2011 COS spectrum, with F122M filter curve overplotted (dashed red line). At upper right, $R(\text{Lo}/\text{Hα})$ (photon flux ratio) in a 0.225 E–W spatial extraction region (orientation indicated on image below) with normalized X-ray flux in blue circles. Emission from the ER prevents a measurement of $R(\text{Lo}/\text{Hα})$ at angles $> \pm 0.5\'r$. $R(\text{Lo}/\text{Hα})$ is elevated toward the regions of brightest X-ray emission. The ACS/SBC F122M Lyα image is shown at bottom (2014 June 21).

(Figure 4, bottom). While the X-ray resolution is not as high as the HST imaging of the ER, there is a clear offset between the X-ray and Lyα profile peaks. Unlike the X-ray and Lyα images, which are brightest in the NW quadrant, the radio image (Zanardo et al. 2014) is brightest in the east.

4.1. The Lyα/Hα Ratio: X-Ray Heating

Neutral hydrogen mass flux and the Lyα/Hα ratio—if all of the high-velocity hydrogen emission originates from collisional excitation as neutral hydrogen atoms cross the RS front, the total flux is proportional to the fluence of hydrogen atoms across the shock boundary. Integrating the individual band images, we calculate the total number of atoms in a given velocity range. We take the total (Galactic + LMC) reddening toward SN 1987 A as a standard ISM curve with $R_V = 3.1$ and $E(B - V) = 0.19$ (see France et al. 2011 for a discussion). The total rate of hydrogen atoms crossing the RS front is approximately

$$N_H = 4\pi d^2 \times F(\Delta \lambda) \frac{\Delta \lambda}{hc} \times P(H)^{-1} \times C_{\text{ISM}},$$

where $d \sim 50$ kpc ($\sim 10\%$ uncertainty; Panagia et al. 1991), $F(\Delta \lambda)$ is the image-integrated flux density in a given band ($\sim 5\%$ uncertainty), $\Delta \lambda$ is the effective bandpass of the filter, $P(H)$ is the number of line photons emitted per atom, and $C_{\text{ISM}}$ is the interstellar attenuation correction factor. $P(H) \approx 0.2$ for Hα and 1 for Lyα (Michael et al. 2003; Heng & McCray 2007).

For the “Hα Blue” image, $\Delta \lambda \approx 100$ Å and $C_{\text{ISM}} = 1.57 \pm 0.08$, giving a total hydrogen fluence of $4.1(\pm 0.7) \times 10^{46}$ atoms s$^{-1}$. For the “Hα Red” image, $\Delta \lambda \approx 120$ Å and $C_{\text{ISM}} = 1.53 \pm 0.08$, giving a total hydrogen fluence of $3.3(\pm 0.5) \times 10^{45}$ atoms s$^{-1}$. Taken together, we estimate the total mass flux of high-velocity hydrogen atoms crossing the RS is $M_H = 7.4(\pm 1.2) \times 10^{22} \text{ g s}^{-1}$ ($1.2 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$).

The analogous calculation using the F122M Lyα image has $\Delta \lambda \approx 100$ Å and $C_{\text{ISM}} = 6.7 \times 1.63$, where 6.7 ($\pm 1.7$) is the correction for dust attenuation and 1.63 ($\pm 0.08$) is the empirically determined correction for the interstellar Lyα line core attenuation. This calculation shows a Lyα-to-Hα photon ratio, $R(\text{Lyα}/\text{Hα})$, of $\approx 17 \pm 6$, a factor of 3.5 larger than attributable to excitation in the RS alone. Therefore, an additional Lyα emission mechanism is present. Note that the reddening correction does not account for differential extinction within the supernova debris, so the intrinsic $R(\text{Lyα}/\text{Hα})$ may be greater. Lyα excess was observed by previous authors using spectroscopic observations of small spatial regions of the SN 1987 A inner ring region (Heng et al. 2006; France et al. 2010).

Combining the “Hα Blue” and “Hα Red” images with the Lyα map, we find the baseline $R(\text{Lo}/\text{Hα})$ interior to the ER is 8–10, at the center and southeastern sides of the inner remnant. $R(\text{Lo}/\text{Hα})$ reaches a maximum on the western and
The northwestern side of the inner remnant where the Chandra emission is brightest (Figure 3). The maximum $R(L_/H_/O)$ is $\sim$35 near PA = 270°, just interior to the brightest X-ray emission from the ER. $R(L_/H_/O)$ values $\sim$20 are found toward PA $\sim$ 60°, the location of the northeast X-ray maximum.

The Role of X-rays—the observed offset between the X-ray and Ly$\alpha$ emitting regions is consistent with the expected separation between the ER and the outer extent of the RS. Following the observation that the dominant energy input in the unshocked supernova debris has evolved from internal heating by radioactive decay to external heating from X-rays produced by unshocked supernova debris has evolved from internal heating to heat the interior. X-rays propagating into the outer debris produce fast photoelectrons, which deposit most of their kinetic energy as heat, provided that the debris has fractional ionization $n_e/m_H > 0.03$ (Xu & McCray 1991). Radiative cooling by thermal excitation of Ly$\alpha$ limits the debris temperature to $T \lesssim 10^4$ K, at which temperature thermal excitation of H$\alpha$ is negligible. Therefore, we expect the Ly$\alpha$/H$\alpha$ ratio to be at a maximum nearest the source of the X-ray heating. The spatial stratification of the Ly$\alpha$ and X-ray emission and the enhanced Ly$\alpha$/H$\alpha$ ratio support the scenario where X-ray heating of the outer debris is responsible for the majority of the observed Ly$\alpha$ emission from SN 1987 A at present.

The total Ly$\alpha$ luminosity in the F122M band is $L_{Ly\alpha} = 2.5 (\pm 0.7) \times 10^{36}$ erg s$^{-1}$, ~70% of which is in excess of the expected RS emission. The total flux of the X-ray ring is $1.04 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, or $L_{X}(0.3–8.0$ keV) = $3.1 (\pm 0.3) \times 10^{36}$ erg s$^{-1}$. However, most of the heating radiation is in the soft X-ray/EUV band (0.01–0.5 keV) which is not observed at earth because of interstellar neutral hydrogen and dust attenuation toward SN 1987 A. Scaling the Zhekov et al. (2006) model X-ray spectrum to the observed days 9885 X-ray/EUV flux, the total 0.01–8.0 keV luminosity is $L_{X}(0.01–8.0$ keV) = $5.6 \times 10^{36}$ erg s$^{-1}$. Assuming that the only source of EUV/soft X-rays is that observed by Chandra and that the neutral hydrogen in the outer ejecta intercepts half of the soft X-rays emitted by the ring, the Ly$\alpha$ heating efficiency must be $\sim$60% to reproduce the F122M image of SN 1987 A. However, slower shocks that contribute more to the optical/UVT emission of the ER than to the X-rays will also be a source of EUV irradiance of the outer debris (Fransson et al. 2013), meaning that the actual soft X-ray heating efficiency is likely substantially lower.

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