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Observing Supernova 1987A with the Refurbished Hubble Space Telescope

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Abstract

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 using the refurbished instruments on HST with data taken in 2004, just before the Space Telescope Imaging Spectrograph failed, we find that the Ly α and H α lines from shock emission continue to brighten, while their maximum velocities continue to decrease. We observe broad blueshifted Ly α , which we attribute to resonant scattering of photons emitted from hotspots on the equatorial ring. We also detect N v $\lambda\lambda$ 1239,1243 Å line emission, but only to the red of Ly α . The profiles of the N v lines differ markedly from that of H α , suggesting that the N⁴⁺ ions are scattered and accelerated by turbulent electromagnetic fields that isotropize the ions in the collisionless shock.

Key words: hydrodynamics – shock waves – supernovae: individual (SN 1987A) – ISM: supernova remnants

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 supernova debris with ambient matter creates a radiating system known as a supernova remnant. SN 1987A (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, 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 (18-23 July 2004) [4], prior to the instrument's failure in August 2004.

The rapidly expanding debris of a supernova 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 into the supernova debris. This double-shock structure propagates outwards until the blast wave encounters a relatively dense obstacle. In the case of SN 1987A, encountering the equatorial ring drives a reflected shock backwards into the debris that merges it with the reverse shock.

The equatorial ring is a relatively dense ($n_H \sim 10^3\text{--}10^4$ atoms cm⁻³) structure of diameter 1.34 light years (ly), inclined at an angle $i = 45^\circ$ with respect to the line of sight [6, 7, 8]. This ring is attributed to a mass loss event that occurred about 20,000 years before the supernova explosion [9, 10]. The first evidence of interaction of the blast wave with the ring appeared in 1995, when a rapidly brightening optical “hotspot” appeared in images taken with the Wide Field Planetary Camera 2 (WFPC2) aboard the HST [11, 12]. Today, the ring is encircled by about 30 hotspots (Fig. 1). The associated on-line movie shows the emergence of these

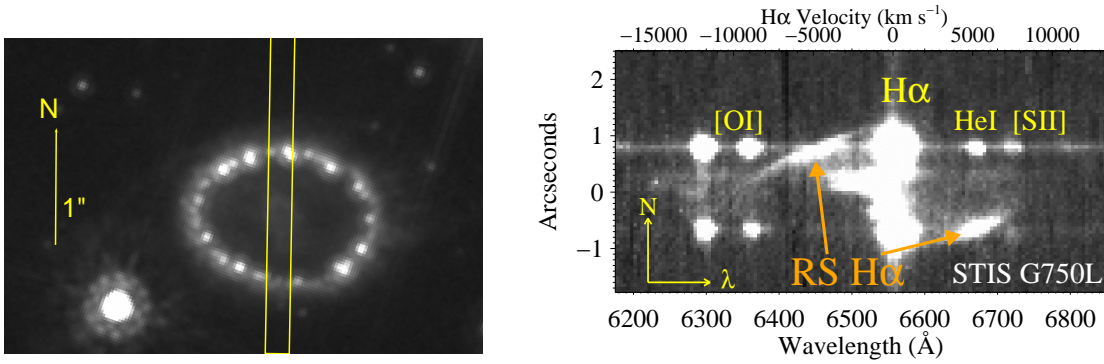


Figure 1: (left) HST-Advanced Camera for Surveys image obtained on 28 November 2003 in the F625W filter with an exposure time of 800s, illustrating the slit orientation used. (right) STIS G750L spectrum of SN 1987A obtained on 31 January 2010, centered about the H α emission line. The vertical bar at the center of the image is stationary H α emission from interstellar or circumstellar gas. The bright spots at the north and south of this bar are the emissions from H α + [N II] $\lambda\lambda 6548, 6583$ Å from hotspots on the equatorial ring. [O I] $\lambda\lambda 6300, 6364$, He I $\lambda 6678$, and [S II] $\lambda\lambda 6716, 6731$ Å emission from the hotspots is also observed. The blueshifted streaks near the center are H α emission excited by radioactivity in the interior of the supernova debris. The curved, blueshifted streak extending from the north side of the vertical bar and the redshifted streak on the south side (noted with orange arrows) are H α emission from the brightest parts of the reverse shock (RS).

hotspots and the expansion of the debris over the past 15 years. The location of these emission spots just inside the ring and their long duration suggests they result from shocks that propagate into dense fingers that protrude inwards from the equatorial ring [13].

Radiation from the reverse shock can be observed at optical and ultraviolet wavelengths. Before it reaches the reverse shock, the outer layer of the supernova debris consists mostly of partially ionized hydrogen and helium gas that has been expanding freely since the explosion. When neutral hydrogen atoms cross the reverse shock, 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 Ly α (1216 Å) and H α (6563 Å) line emission. On average, approximately 1 Ly α photon and 0.2 H α photons are produced for every hydrogen atom crossing the reverse shock [14, 15, 16].

The emission properties of the reverse shock 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]. The difference is that, in other collisionless supernova remnants the blast wave overtakes nearly stationary circumstellar matter, while in SN 1987A fast-moving hydrogen gas in the supernova debris overtakes the reverse shock. As the hydrogen atoms in the supernova debris cross the reverse shock, they freely stream with radial velocity $v_r = r/t_e$, where r is the radius of the reverse shock 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 supernova 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 we observe (Fig. 1) correspond to the projected ballistic velocity of the unshocked supernova debris.

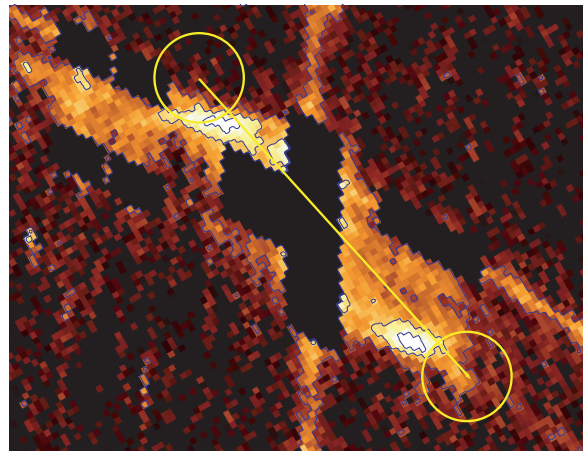
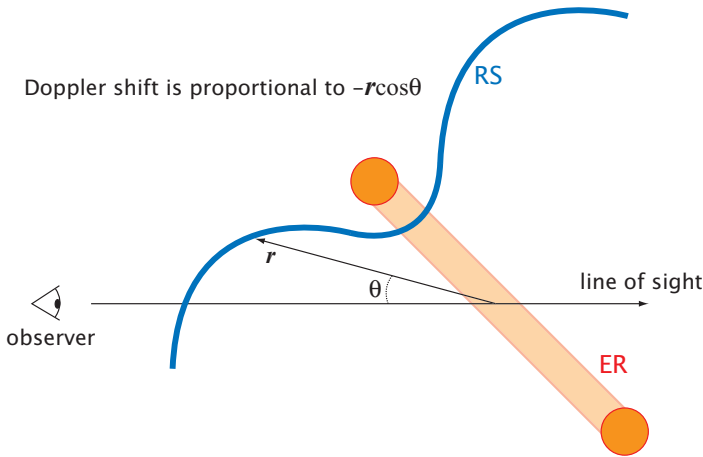


Figure 2: (left) Schematic illustration of the location of the reverse shock (RS) with respect to the equatorial ring (ER), which is inclined 45° to the line of sight. (right) H α emission from the reverse shock transformed into a cross-sectional view through the circumstellar ring (see text). The diameter of the equatorial ring is 1.34 ly. The left and right yellow circles represent the near (N) and far (S) 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.

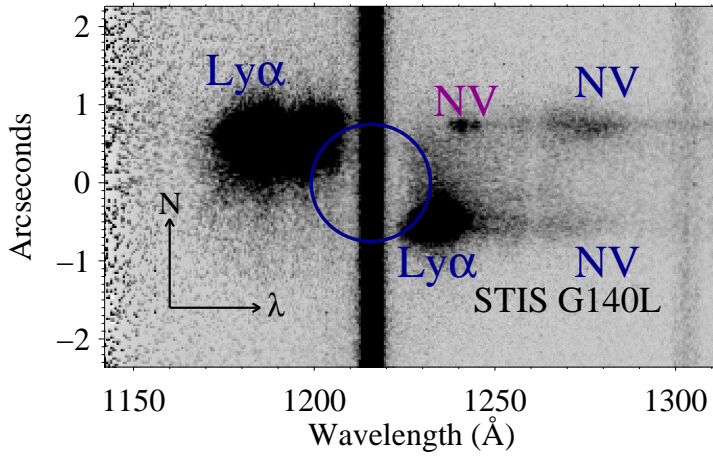


Figure 3: *STIS* G140L observations of SN 1987A, acquired on 31 January 2010. The bright vertical stripe is the slit image in geocoronal $\text{Ly}\alpha$. The blue ellipse approximates the location of the circumstellar emission ring. Broad, faint features seen on the north and south sides between ~ 1260 – 1290 Å (labeled N v in blue) are produced by nitrogen ions in the reverse shock, and the shock-excited N v hotspot emission is labeled in magenta.

The unique mapping between distance along the line-of-sight and Doppler shift allows us to convert the spectrum of Figure 1 into a map of the location of the reverse shock (Fig. 2). The $\text{H}\alpha$ emission is concentrated just inside the equatorial ring because at these locations the reverse shock penetrates into denser regions of the supernova envelope, where the flow is held back by shocks reflected from the ring. The net $\text{H}\alpha$ flux observed through the $52'' \times 0.2''$ slit in the total reverse shock (northern blueshifted plus southern redshifted streaks, Fig. 1) is $3.3 (\pm 0.5) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ [19]. This value is a factor of about 1.7 greater than that measured in July 2004 [4] and February 2005 [20].

Unlike $\text{H}\alpha$ photons, $\text{Ly}\alpha$ photons experience resonant scattering by hydrogen atoms. Thus, $\text{Ly}\alpha$ 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 scans of the $\text{Ly}\alpha$ (the dark streaks in Figure 3) and $\text{H}\alpha$ (the bright streaks in Figure 1) emission from the reverse shock. The observed $\text{H}\alpha$ and $\text{Ly}\alpha$ fluxes have been increased by factors ≈ 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 $\text{Ly}\alpha$ to $\text{H}\alpha$ photon fluxes has a fairly constant value near 40 for velocities between -2500 km s^{-1} 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 $\text{H}\alpha$ emission fades for blueshift velocities $< -8,000 \text{ km s}^{-1}$, while the $\text{Ly}\alpha$ emission remains bright to blueshift velocities approaching $-12,000 \text{ km s}^{-1}$. If the $\text{Ly}\alpha$ photons are produced by the same mechanism as the $\text{H}\alpha$ photons, then the $\text{Ly}\alpha$ to $\text{H}\alpha$ ratio should be the same for all observed velocities; but it is not. Therefore, most of the observed $\text{Ly}\alpha$ emission cannot be produced directly by hydrogen atoms crossing the reverse shock. Unlike $\text{H}\alpha$, the broad $\text{Ly}\alpha$ emission is not confined to a narrow strip delineating the reverse shock surface (Fig. 3).

We propose a different mechanism to account for the highly blueshifted $\text{Ly}\alpha$ emission. As the supernova blast wave enters the equatorial ring, the shocked hotspots on the ring become bright sources of $\text{Ly}\alpha$ 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 ($\Delta v < 300 \text{ km s}^{-1}$) [8, 13], so that it is entirely blocked by the interstellar medium. Roughly half of this radiation propagates inwards into the supernova debris, where the $\text{Ly}\alpha$ photons may be resonantly scattered by hydrogen atoms that are expanding with radial velocities ranging from 3000 km s^{-1} to 9000 km s^{-1} . In the rest frame of the hydrogen atoms in the expanding debris, photons propagating inwards are blueshifted. If they are then scattered backwards towards Earth, they will be blueshifted a second time. There is no corresponding bright, high-velocity, redshifted $\text{Ly}\alpha$ component on the south side of the equatorial ring (Figs 3, 4). The $\text{Ly}\alpha$ photons which are emitted radially inwards by the ring hotspots 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 towards the observer receive a redshift that cancels out this blueshift. This leaves the $\text{Ly}\alpha$ 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 $\text{Ly}\alpha$ photons are emitted by the hotspots to account for the observed high-velocity $\text{Ly}\alpha$ and that the neutral hydrogen layer in the expanding supernova envelope has sufficient optical depth to scatter $\text{Ly}\alpha$ photons by roughly half of the observed maximum velocity, *i.e.*, 6000 km s^{-1} . It is not possible to measure the emitted $\text{Ly}\alpha$ flux from the hotspots directly because this radiation is blocked by interstellar hydrogen atoms. We can estimate the strength of $\text{Ly}\alpha$ emission using the direct $\text{H}\alpha$ emission from the ring, applying a theoretical scaling ($\text{Ly}\alpha:\text{H}\alpha \sim 5 - 10$; [23]). The $\text{H}\alpha$ hotspot emission within the *STIS* slit in the 2010 observations ($\approx 2.1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$) suggests that the hotspot $\text{Ly}\alpha$ flux in 2010 is approximately $3\text{--}7 \text{ photons cm}^{-2} \text{ s}^{-1}$. This is sufficient to account for the broad blueshifted $\text{Ly}\alpha$ emission (Fig. 4).

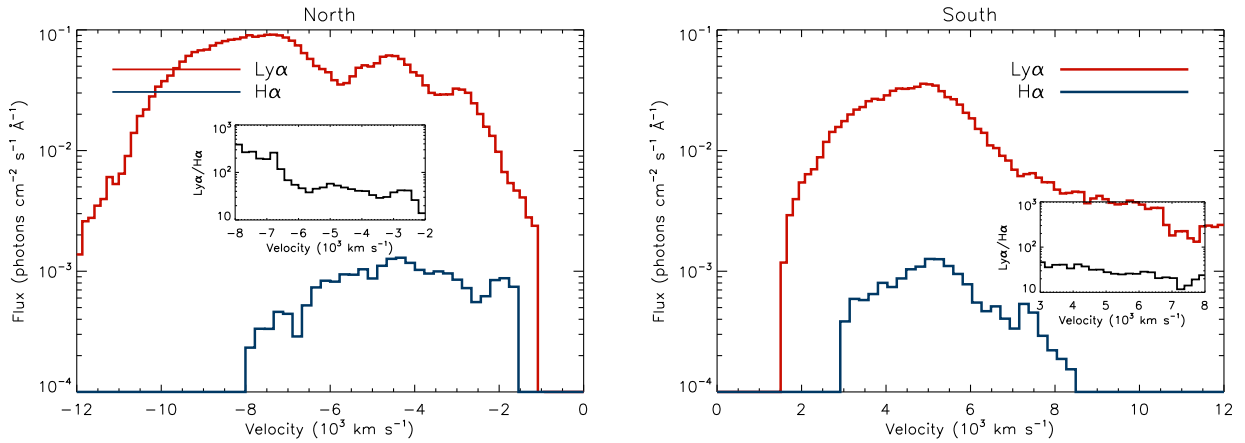


Figure 4: (*left*) Integrated H α and Ly α emission from the reverse shock on the north side of the equatorial ring. While the H α emission approaches zero blueward of -8000 km s^{-1} , it has been artificially truncated in this plot because of strong contamination from [O I] $\lambda\lambda 6300, 6364 \text{ \AA}$ present in the hotspot (Fig. 1). The inset shows the ratio of Ly α to H α . The broad dip in the Ly α emission near -6000 km s^{-1} may be due to absorption by interstellar Si II ($\lambda\lambda 1190, 1193 \text{ \AA}$). Interstellar absorptions from Si II ($\lambda\lambda 1190, 1193 \text{ \AA}$, $\lambda\lambda 1260, 1265 \text{ \AA}$ and $\lambda\lambda 1526, 1533 \text{ \AA}$) are clearly detected on the sightline to a nearby star. (*right*) Velocity profiles for the southern, redshifted emission. We truncate the southern H α profile at $v \geq 8500 \text{ km s}^{-1}$ because the H α flux at these velocities is consistent with a combination of detector background and [S II] emission scattered inside of the equatorial ring radius.

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

The Ly α emission brightened from 2004 to 2010 (Fig. 5). We observe two primary features: (a) the Ly α emission has increased in brightness by factors of 1.6–2.4 for the North and South shock emission, and (b) the maximum Doppler shift in the northern blue shifted Ly α emission is decreasing as a function of time. Note also the faint glow seen on the north and south sides at wavelengths ranging from $\sim 1260\text{--}1290 \text{ \AA}$, also visible in Figure 3. This emission cannot be attributed to Ly α , because it would require the Ly α emission on the north side to be redshifted by velocities up to $+20,000 \text{ km/s}$, while the actual Ly α 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 reverse shock. Neutral or singly-ionized nitrogen atoms that cross the reverse shock 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 2 P fine-structure state and emit a N v 1239 \AA or 1243 \AA photon, or it may be ionized to N $^{5+}$. The number of N v photons produced, per nitrogen atom passing through the reverse shock, will be equal to the ratio of the N $^{4+}$ 2 2 P excitation rate to its ionization rate. The Ly α 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 reverse shock will emit ~ 600 N v photons before it becomes fully ionized. Given the enriched abundance of nitrogen (N/H $\sim 2 \times 10^{-4}$) [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 reverse shock 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 significantly from free expansion when they emit Ly α . If our identification of this faint feature as N v is correct, we are seeing redshifts on the north side extending to $\sim 12,000 \text{ km s}^{-1}$. 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 $\sim -12,000 \text{ km s}^{-1}$. We cannot discern this wing because it will be buried under the much brighter Ly α emission. A critical test of our hypothesis will be the observation of the profile of the C iv $\lambda\lambda 1548, 1550 \text{ \AA}$ doublet, which we estimate to have a brightness ~ 0.3 times that of N v $\lambda\lambda 1239, 1243 \text{ \AA}$. The C iv doublet should have the same intrinsic emission profile as N v, but it will not be

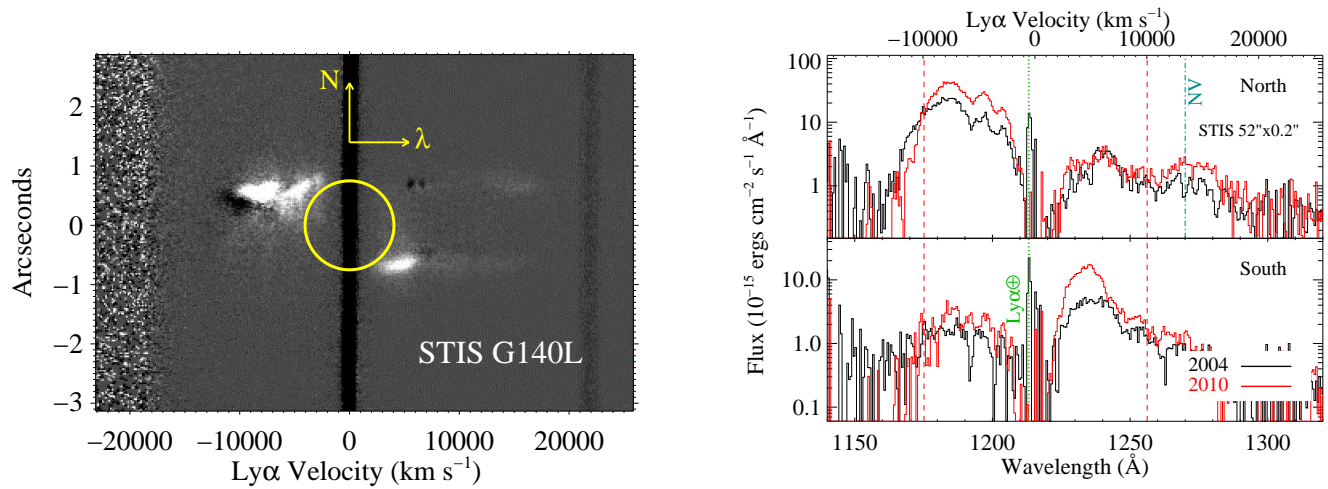


Figure 5: (*left*) $\text{Ly}\alpha$ 2010-2004 difference image, scaled such that gray indicates similar intensities in the two epochs. The yellow circle approximates the location of the circumstellar emission ring. (*right*) One-dimensional spectra of the $\text{Ly}\alpha$ emission from the North and South regions [27]. The narrow feature labeled “ Θ ” is residual emission from Earth’s upper atmosphere.

confused with $\text{Ly}\alpha$ emission and absorption.

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- [28] K.F. thanks Matthew 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, Incorporated, under NASA contract NAS5-26555.

1. Supplementary Material

On-line hotspot movie caption: [This movie displays the evolution of the remnant of SN1987A as observed by the *Hubble Space Telescope*. The rapidly fading and expanding central source is light from the inner radioactive supernova debris. The inner circumstellar ring is glowing initially because it was ionized by radiation from the supernova outburst. At about 1995, the first hotspot appeared at approximately 11 o’clock. Today, the ring is entirely encircled by hotspots. The radiation from the hotspots is

caused by compression and heating that takes place when the supernova blast wave enters fingers of dense gas protruding inwards from the circumstellar ring.]