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HST OBSERVATIONS OF YOUNG, OXYGEN-RICH SUPERNOVA REMNANTS

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RESUMEN

Las observaciones de las remanentes de supernova jóvenes hechas con el *Observatorio Espacial Hubble* (*HST*) ofrecen una resolución espacial exquisita y acceso a las frecuencias ultravioletas para hacer investigaciones espectroscópicas y de imágenes. Resalto estudios recientes hechos con el *HST* que aislan los nudos y filamentos no contaminados del gas expulsado por la explosión para estudiar las regiones de enfriamiento post choque y el desarrollo de las inestabilidades, y para determinar las abundancias de los elementos en los residuos de alta velocidad que resultan de la explosión de supernova. Resumo los resultados para los remanentes Cas A en nuestra galaxia, N 132D y SNR 0540−69.3 en la Nube Mayor de Magallanes y 1E 0102.2−7219 en la Nube Menor de Magallanes.

ABSTRACT

Hubble Space Telescope (*HST*) observations of young supernova remnants offer exquisite spatial resolution and access to ultraviolet wavelengths for imaging and spectroscopic investigations. I highlight recent *HST* studies that isolate uncontaminated ejecta knots and filaments for studying post-shock cooling regions and the development of instabilities, and determining elemental abundances in the fast-moving supernova debris. I summarize results for Cas A in the Galaxy, N 132D and SNR 0540−69.3 in the Large Magellanic Cloud, and 1E 0102.2−7219 in the Small Magellanic Cloud.

Key Words: **SUPERNOVA REMNANTS**

1. INTRODUCTION

The products of nucleosynthesis that are formed deep within the cores of massive stars are generally hidden from our scrutiny until the stars explode as supernovae. Young supernova remnants (SNRs) allow us to investigate material from the cores of massive stars directly, leading to observational tests of theories for stellar evolution, nucleosynthesis, and the chemical enrichment of the ISM in galaxies. There are only eight young SNRs known which contain fast-moving ($> 1000\,\mathrm{km\,s^{-1}}$) optical filaments of uncontaminated debris; Cas A in our Galaxy is the prototype of this class. The highly elevated abundances of O, Ne, and other heavy elements suggest these debris originated within the helium-burnt layers of massive ($> 10\,M_{\odot}$) progenitor stars.

One important goal of our study of O-rich SNRs is to pin down the progenitors based on the chemical composition and mass of the SN debris. We can then extrapolate the metal production rates based on observed stellar luminosity functions. In addition, SNRs are rich laboratories for studying the physics of shock waves as the supernova debris interact with their circumstellar environments.

2. CASSIOPEIA A

Cassiopeia A (Cas A; SN $\simeq 1680$) is currently the youngest known Galactic SNR. Mass estimates for the progenitor range between 10 and $30\,M_{\odot}$. Elevated abundances of O-burning products in the remnant's "fast-moving knots" (or "FMKs"), the presence of much slower moving He- and N-rich clumps ("quasi-stationary flocculi" or "QSFs") of circumstellar material (Chevalier & Kirshner 1978, 1979), and the presence of N-rich, high-velocity outer ejecta (Fesen, Becker, & Blair 1987; Fesen 2001) have prompted several researchers to suggest the Cas A progenitor may have been a WN-type Wolf-Rayet star that experienced substantial mass loss before exploding as a Type Ib/c or Type II supernova.

The optical emission from Cas A is mostly confined to a shell of $\sim 2'$ radius that expands at up to $6000\,\mathrm{km\,s^{-1}}$. The FMKs exhibit strong O, S, and Ar

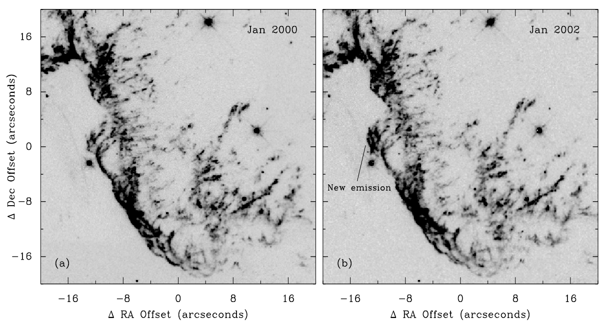

Fig. 1. WFPC2 F675W images of a section of the NW rim of Cas A at two epochs showing primarily [S II] λ 6716, 6731 emission. The center of the SNR is toward the lower-left and the ejecta move to the upper-right. (*a*) The January 2000 image shows wavy filaments at the reverse shock at the onset of radiative cooling, and the development of Rayleigh-Taylor-like fingers that protrude radially in the direction of the flow. (*b*) The January 2002 image shows $\sim 1''$ ejecta proper motions toward the upper-right and new emission filaments, indicating short cooling times in the metal-rich gas.

lines, and are thought to represent uncontaminated ejecta that have been heated and compressed by the reverse shock. The ejecta are often distributed in ring-like structures on the surface of the expanding shell (e.g., Lawrence et al. 1995).

Fesen et al. (2001) presented images of the optically emitting ejecta in Cas A otained with WFPC2 aboard the *Hubble Space Telescope* (*HST*). A mosaic of the SNR was contructed from broad-band (F450W, F675W, F850LP) images that captured the entire velocity range from the strong emitting species [O III] λλ 4959, 5007, [S II] λλ 6716, 6731, and [S III] λ 9532. The images allowed us to discern details down to the resolution limit of *HST* ($\sim 0''\!.1 \approx 5 \times 10^{15}$ cm), revealing complex ionization structure and chemical fractionation within the ejecta. F658N images were used to distinguish slow-moving, N-rich QSFs from the high-velocity debris.

Figure 1 shows the extraordinary detail revealed by WFPC2 in a bright filament on the NW rim of the optical shell. The reverse shock is located at the lower-left array of intertwined or corrugated filaments toward the interior of the SNR and the ejecta expand toward the upper-right. Although additional imaging is needed to monitor this and other similar regions, the morphology suggests an evolution from relatively wavy filaments oriented parallel to the reverse shock to knotty, radial features away from the shock. The progression may show the formation of radiative and hydrodynamic instabilities, as seen in numerical simulations of shock-cloud interactions (e.g., Klein, McKee, & Colella 1994). In

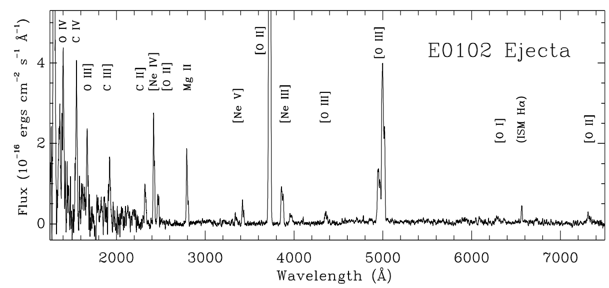

Fig. 2. UV/optical spectrum of ejecta in E0102 obtained with the *HST* FOS through the $0''\!.86$ square aperture (from Blair et al. 2000). Only lines of O, C, Ne, and Mg are detected in the fast debris. Faint Hα emission arises from photoionized gas around the SNR.

the right panel of Fig. 1, we show a second epoch image obtained two years later, where a new filament has emerged from the reverse shock at the labeled position and noticeable changes have occurred along the wavy filaments. We thus are able to identify the location of the reverse shock and establish that the cooling time for these optical filaments is extremely short, as predicted by models of shocked metal-rich gas (e.g., Dopita, Binette, & Tuohy 1984).

3. N 132D AND E0102

The young SNRs N 132D in the Large Magellanic Cloud (LMC) and 1E 0102.2−7219 (hereafter E0102) in the Small Magellanic Cloud (SMC) are important both because of their similarities to Cas A and because of their differences. Their distances are known, they can be studied with *HST* at UV wavelengths due to their low reddening, and their ages have been derived (~ 2500 yrs for N 132D; ~ 1000 yrs for E0102) from the ejecta kinematics. Each SNR shows a forward/reverse shock structure; E0102 appears dynamically very similar to Cas A. However, the ejecta in N 132D and E0102 are peculiar for showing UV/optical line emission from C, O, Ne, and Mg *only* (e.g., Blair et al. 2000), but no emission from the O-burning or Si-burning products S, Ca, Ar, etc., that are seen in Cas A. Figure 2 shows the UV/optical spectrum of the E0102 ejecta obtained with FOS aboard *HST*. Additional emission lines from O, Ne, Mg, and Si are observed in the X-rays in E0102 (see Ballet 2003).

E0102 and N 132D differ by a factor of three in dynamical age, and both are much older than Cas A, so it seems that evolutionary effects—such as variable depths to which the reverse shock has penetrated into the ejecta—do not account for the two types of O-rich SNRs. The differences probably arise due to different types of progenitor stars.

Blair et al. (2000) used a modified version of the Raymond & Smith (1977) shock code to model the FOS emission-line fluxes and *ASCA* spectrum of E0102 to derive the relative abundances. For N 132D the ratios were: $N(\mathrm{O})/N(\mathrm{C}) = 32$, $N(\mathrm{O})/N(\mathrm{Ne}) = 5.6$, $N(\mathrm{O})/N(\mathrm{Mg}) = 20$ to 40, $N(\mathrm{O})/N(\mathrm{Si}) = 90$ to 100. For E0102 the ratios were: $N(\mathrm{O})/N(\mathrm{C}) = 16$, $N(\mathrm{O})/N(\mathrm{Ne}) = 3.2$, $N(\mathrm{O})/N(\mathrm{Mg}) = 10$ to 20, $N(\mathrm{O})/N(\mathrm{Si}) = 45$ to 50. Comparing these ratios to yields predicted by nucleosynthesis models indicates that the progenitor stars were probably in the 25 to $35\,M_{\odot}$ range. However, the best matches appear to be with models for massive O-rich mantles in Wolf-Rayet W/O stars, and we speculate that these were Type Ib SN explosions.

4. SNR 0540−69.3

SNR 0540−69.3 (hereafter SNR0540) in the LMC shares traits with two prototype objects: Cas A and the Crab Nebula. The ejecta have abundances that resemble those seen in Cas A, with enhanced O, S, Ar, and other heavy elements indicating their origin in the nuclear processed core of a massive star. SNR0540 is also the only object in the O-rich class with an active (50 ms) pulsar and synchrotron nebula that has been detected at X-ray, optical, and radio wavelengths; hence, is often called “Crab-like”. Kirshner et al. (1989) noted that SNR0540 lies at a projected distance of only 400 pc from SN 1987A and is from the same generation of star formation. They derived a kinematic age of ~ 760 yrs (compared to ~ 1500 yrs from the pulsar spin-down rate), which probably makes it the most recent predecessor to SN 1987A in the LMC. Caraveo et al. (1998) suggested that some material in the optical shell may be the remains of a ring ejected by the progenitor star, strengthening the possibility that SNR0540 may closely foreshadow the evolution of SN 1987A.

Figure 3 shows WFPC2 images through emission-line filters and a broad continuum filter. These are compared to the *Chandra* HRC image of Gotthelf & Wang (2000) in the lower-right panel. There is a stark resemblance to the Crab Nebula with the similarities between the optical and X-ray continuum images of the synchrotron nebula, which suggest a torus plus jet-like morphology. In addition, an [O III] skin envelopes the filamentary [S II] emission, best seen in the difference image of the middle-left panel.

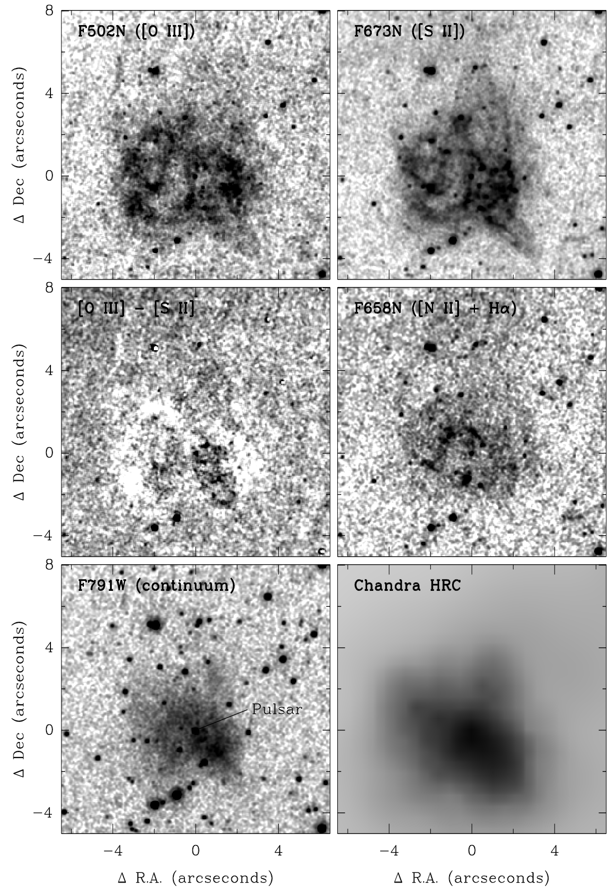

Fig. 3. WFPC2 images of SNR0540 in several emission lines plus a broad continuum filter. The *Chandra* HRC image is shown in the lower-right panel.

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