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DISCOVERY OF OPTICAL EMISSION FROM THE REMNANT OF SN 1957D IN M83

KNOX S. LONG[1,2] AND WILLIAM P. BLAIR[2]
Center for Astrophysical Sciences, The Johns Hopkins University
AND
WOJCIECH KRZEMINSKI
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington
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ABSTRACT

Using the 2.5 m DuPont telescope at Las Campanas Observatory, we have obtained images of the inner portion of M83 including the region surrounding the site of SN 1957D using narrow-band interference filters centered on lines of Hα, [S II], [O I], and [O III], as well as a continuum band centered at 6100 Å. At the position of the recently recovered radio source, there is now a nebula bright in [O III], but also visible in [S II], [O I], and Hα. Spectroscopy of the nebulosity shows that the [O III] λλ4959, 5007 lines are broad—$\sim$2500 km s^{-1} (FWHM)—confirming that the emission nebula is due to the supernova and indicating that the explosion was that of a massive star. This object is the newest and certainly the youngest addition to the class of ejecta-dominated supernova remnants such as Cas A. There is no evidence of emission from any of the four other historical supernovae in M83.

Subject headings: nebulae: supernova remnants — nucleosynthesis — stars: supernovae

I. INTRODUCTION

Nearly all supernovae (SNs) are discovered optically since at maximum light a supernova competes with the total optical luminosity of a galaxy, but the light from a SN fades rapidly and most are lost within a year of discovery. The light output from a SN rises again, however, as the ejecta from the exploded star interacts with the surrounding interstellar and circumstellar medium. The rate at which the SN, now a supernova remnant (SNR), evolves depends upon the density of the surrounding medium. Most observed SNRs are thousands of years old. The youngest historical SN in our Galaxy that has been recovered as a SNR is Cas A which is now $\sim$310 yr old (Fesen, Becker, and Blair 1987); for historically observed extragalactic SNs, none had been recovered unambiguously at optical wavelengths until now, when three have been discovered almost simultaneously (Stringfellow *et al.* 1988; Fesen and Becker 1988; Long, Blair and Krzeminski 1988), including the one discussed in detail here.

It is important to recover SNRs early. That is when the ejecta from the pre–SN star are least mixed with the interstellar medium and therefore that is when the raw products of nucleosynthesis should be most clearly visible. Additionally, the time history of the rise of very young SNRs at various wavelengths should provide strong constraints on models of the physical processes in young SNRs and on the very local environment of the stellar explosion.

Although the transition from SN to SNR has never been observed, recent advances in detectors have made it possible to monitor some SNs spectroscopically for periods longer than a year (Uomoto and Kirshner 1986; Schlegel and Kirshner 1989). Instead of a continuum with absorption lines, these late-time spectra show the onset of a nebular phase, with broad, low-excitation emission lines such as [O I] and Hα (depending on SN type). The emission is still photoionization-driven rather than shock-driven, in contrast with most SNRs. Additionally, some SNs have been observed at radio wavelengths for extended periods of time. The radio emission is most likely due to the interaction of the SN shock wave with a substantial circumstellar medium, although pulsar-driven mechanisms are also a possibility (Weiler *et al.* 1986).

At a distance of 3.7 Mpc (de Vaucouleurs 1979), M83 is a nearly face-on ($i \sim 24°$) SAB(s)c galaxy with well-developed spiral arms which support a prodigious amount of star formation and interarm regions which appear devoid of young stars (Jensen, Talbot, and Dufour 1981). Five historical SNs have been observed in M83, more than any other galaxy except NGC 6946.

SN 1957D in M83 was not well observed. It was discovered well past maximum light and its type was not accurately determined; there is no published spectrum. It was located on the inner edge of a prominent spiral arm of the galaxy ($2\overset{'}{.}3$ or 2.5 kpc NE of the nucleus). Pennington, Talbot, and Dufour (1982) suggest, on the basis of the integrated colors in the region surrounding SN 1957D, that the SN was produced by a massive Population I progenitor. In an early attempt to recover radio remnants in M83, Cowan and Branch (1982) found a radio source about 1′ from the published position of SN 1957D. Subsequently, Pennington and Dufour (1983) remeasured the position of the SN from archival plates, and found that the actual position of the SN was within 3″ of the radio source. Further VLA observations by Cowan and Branch (1985) have shown the radio source to be nonthermal and thus the association of the SN with the radio source appears secure.

Recently, as part of a more general CCD/interference filter search for SNRs in external galaxies, we have observed M83, including the region around SN 1957D. In this *Letter*, we report these imaging observations as well as spectroscopic observations of the source that we identify as the optical remnant of SN 1957D.

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[1] Adjunct Associate, Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington.

[2] Guest Observer, Las Campanas Observatory, operated by the Carnegie Institution of Washington.

II. OBSERVATIONS

The imaging observations were carried out at Las Campanas Observatory in 1987 April using the 2.5 m DuPont telescope, a focal plane reducer, interference filters and a TI 800 × 800 CCD. With this instrument configuration, the full field is 5′.5 and each pixel subtends 0″.41. The characteristics of the interference filters are summarized in Table 1. The choice of filters was dictated largely by our survey technique for locating older SNRs (cf. Long *et al.* 1988). The [O III] filter was included because a small number of SNRs, such as N132d in the Large Magellanic Cloud (Lasker 1980) and the SNR in NGC 4449 (Kirshner and Blair 1980; Blair, Kirshner, and Winkler 1983) show very strong [O III] emission from shocked ejecta.

The 1000–3000 s exposures were centered on the nucleus. Conditions were good on the first night when [O III], Hα, and continuum observations were made, but on the second night, when the [S II] and [O I] exposures were taken, there was substantial cirrus. The seeing was quite good—0″.9–1″.1, except for the [O I] image in which the star images are $\sim$1″.3 (FWHM). The images were reduced with IRAF and flux-calibrated where appropriate. Reproductions of the Hα, [S II], [O III], continuum, and [O I] images in the vicinity of SN 1957D are shown in Figure 1 (Plate L2). A comparison of the Hα and continuum images reveals a number of H II regions in the spiral arm which cuts across the pictures from NE to SW. A dust lane is clearly visible along the SE edge of the spiral arm. At the position of the radio SNR there is an emission nebula which is barely present in the [S II], [O I], and Hα images, bright in the [O III] image, but nearly absent from the continuum image. The diameter of the nebula in the [O III] image is consistent with that of an unresolved source. The ratio of [O III] to Hα is very high ($\sim$10) compared with that of a typical H II region ($<$0.25) in the image. The total flux through the [O III] filter from the nebula is $\sim 2 \times 10^{-14}$ ergs cm^{-2} s^{-1}.

The sites of all five historical SNs in M83 lie within our CCD images. We have carefully inspected the positions of all the historical SNs and of all the nonthermal radio sources reported by Cowan and Branch (1985) both by blinking the raw images and using continuum subtraction and ratio software developed for our SNR search program. None except SN 1957D has an obvious optical counterpart.

In order to confirm that we had recovered the remnant of SN 1957D, we then observed the object spectroscopically. Initial observations were carried out in 1988 May on the DuPont telescope with the Boller & Chivens (B&C) spectrograph and an intensified CCD (2D-Frutti) detector using a 1200 line mm^{-1} grating blazed at 5000 Å. These observations cover the spectral range 3500 Å to 5500 Å (although the sensitivity decreases substantially below 3700 Å). This provided a spectral resolution of 2.9 Å (FWHM) and a spatial resolution along the slit of $\sim$4″; data are digitized to an accuracy of 0.67 Å in the dispersion direction and 1″.4 along the slit. A total of 23,600 s of data were obtained with a slit 3″.25 × 1″.7 oriented with the slit N-S on the sky. The data show the presence of narrow lines of [O II] λλ3727, 3729, Hβ, and [O III] λλ4959, 5007 near the position of the nebulosity and peaking north of the SNR. There is also evidence of broad line emission at [O III] in the raw images.

TABLE 1

INTERFERENCE FILTER CHARACTERISTICS

Name	λ_c (Å)	Δλ (FWHM [Å])	$T_{\rm peak}$
[O III]	5028	53	68%
Continuum	6100	150	65
[O I]	6313	50	57
Hα	6575	52	62
[S II]	6737	57	51

In 1988 August we obtained a red spectrum at the position of the nebulosity using the DuPont telescope with the Modular Spectrograph, a newly commissioned long-slit CCD spectrograph designed by Paul Schechter. For these observations we used the f/1.4 camera which yields a plate scale of 0″.8 pixel^{-1}. With the 600 line mm^{-1} grating, the spectrograph has a dispersion of 3 Å pixel^{-1}. The spectrum covers the wavelength range 4800–7200 Å and has a spectral resolution of 10 Å (FWHM); the spatial resolution along the slit is $\sim$2″. The 8′ long slit was oriented N-S and widened to 3″ to ensure the inclusion of the SN. Seeing conditions were not ideal ($\sim$1″.5) because of the relatively high air mass (1.3–1.7). As was the case for the B&C/2D-Frutti spectra, the raw spectra show broad emission near [O III] λλ4959, 5007 and narrow lines (Hα, [S II] λλ6717, 6731, [O III] λλ4959, 5007) from extended diffuse emission line gas to the north of the SN position.

Both sets of data were reduced and calibrated using the IRAF long-slit reduction package and standard procedures. Subsequently one-dimensional spectra were extracted from the two-dimensional images. For these extractions background regions were defined immediately adjacent to the SNR which (in both sets of data) is clearly present in only two lines of the images. Background subtraction is difficult for this object because both the galaxy background and the diffuse emission line gas are rapidly varying along the slit. The extracted spectra are shown in Figures 2 and 3 for the blue data and Figure 4 for the red spectrum. The only feature which can be attributed unambiguously to the SNR is the broad feature near [O III] λλ4959, 5007. There may also be emission from [O II] λλ3727,

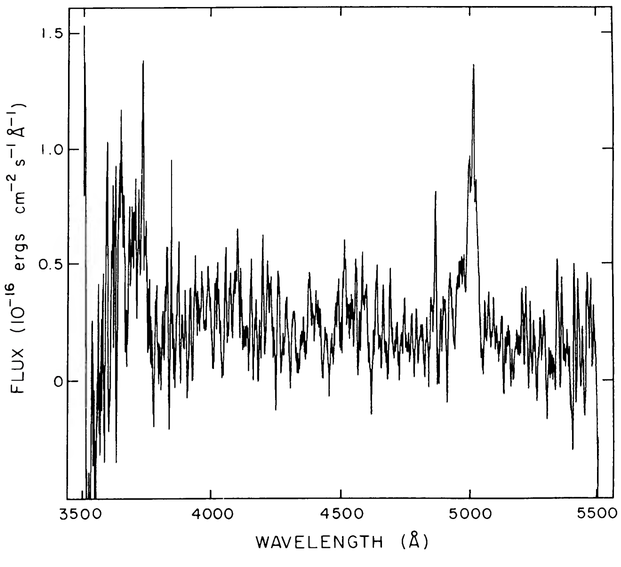

FIG. 2.—The blue spectrum of the nebulosity at the site of SN 1957D as observed with the B&C spectrograph and 2D-Frutti. The only lines from the remnant of SN 1957D are at [O III] λλ4959, 5007 which are broad compared with the instrumental resolution.

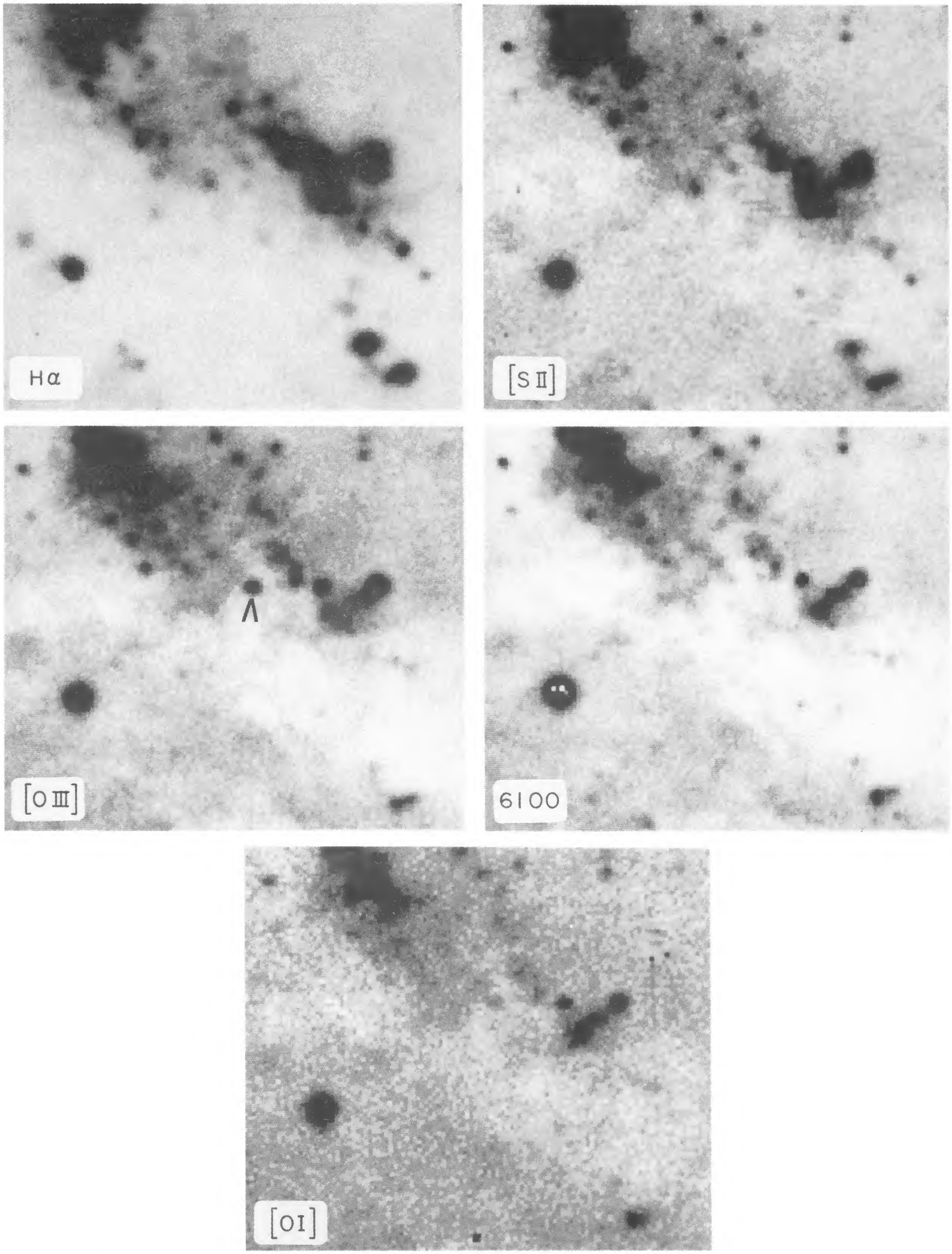

FIG. 1.—A mosaic consisting of the region surrounding the site of SN 1957D through (*top left*) Hα, (*top right*) [S II], (*center left*) [O III], (*center right*) continuum, and (*bottom*) [O I] filters. The contrast has been adjusted so that stars are roughly comparable. The size of the panels is ~1′. North is up, and east is to the left. The source we identify with SN 1957D is indicated on the [O III] image.

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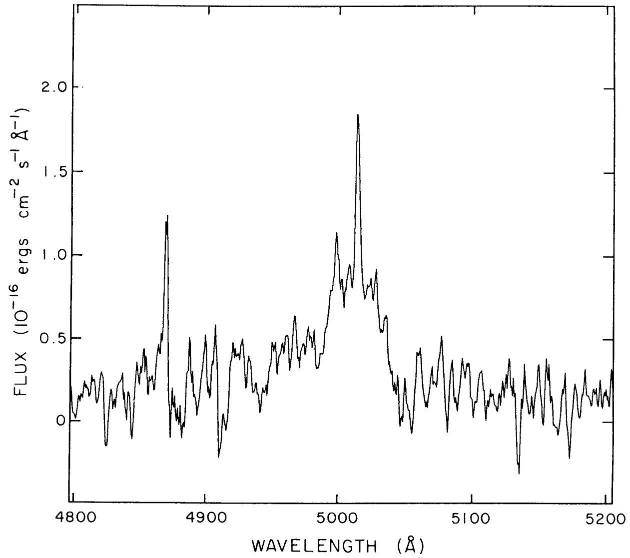

FIG. 3.—Enlargement of the region of Fig. 2 surrounding [O III] λλ4959, 5007. Additional smoothing has been applied. The broadened [O III] lines are clearly present in approximately the expected ratio.

3729 in the blue spectrum, but in view of the decreasing sensitivity of the B&C spectrograph/2D-Frutti system near 3700 Å we choose to interpret this feature as an upper limit. An expanded view of the [O III] line region from the blue spectrum is shown in Figure 3. Deconvolution of this spectral feature yields a total flux of 6×10^{-15} ergs cm^{-2} s^{-1} with a FWHM for an individual line of 38 Å in the blue spectrum and a flux of 4×10^{-15} ergs cm^{-2} s^{-1} and FWHM of 44 Å in the red spectrum. (Given the difficulty of the background subtraction for both imaging and spectroscopy and the quality of the spectra, the mild disagreement between the flux values obtained from the imagery and spectroscopy is not surprising.) We cannot place very restrictive limits on the broad components for other lines; from the Modular Spectrograph data shown in Figure 4, [O I] λ6300, Hα, and [S II] λλ6717, 6731 would have been seen at ~20% of the strength of [O III], while [O II] λλ3727, 3729 would have been seen only if it were comparable to or stronger than [O III]. Notice that in the blue spectrum narrow Hβ is slightly undersubtracted, whereas in the red spectrum narrow Hβ is slightly oversubtracted. There is in fact narrow Hα, Hβ, and [S II] superposed on the position of the SNR. In the diffuse narrow-line gas, the ratio of narrow [S II] λ6717:[S II] λ6731 is 1.39, near the low-density limit; the ratio of narrow [S II] λ6717 + [S II] λ6731:Hα is 0.25, consistent with the presumption that the narrow-line emission is due to photoionized gas. There is no strong reason to associate the narrow-line emission with the SNR directly, although we reiterate that the [S II], [O I], and Hα images in Figure 1 do show a small enhancement coincident with the [O III] point source.

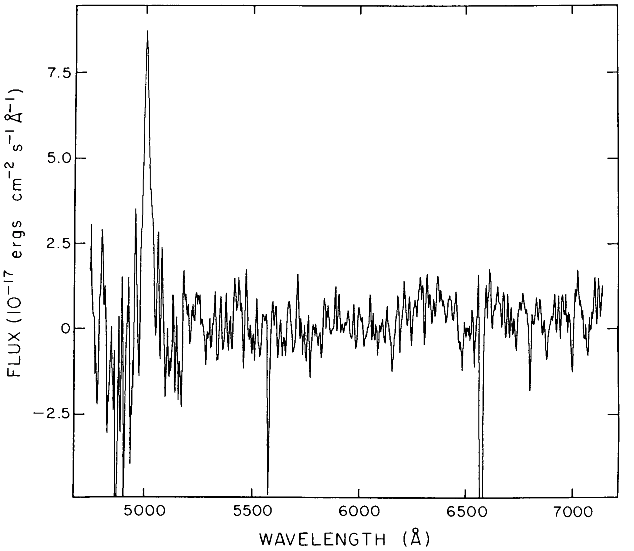

FIG. 4.—The red spectrum of the remnant of SN 1957D obtained with the Modular Spectrograph. Broad-line emission from [O III] λλ4959, 5007 is apparent, but no emission is detected at [O I] λ6300, Hα λ6563, or [S II] λ6725.

III. DISCUSSION

The remnant of SN 1957D is one of only three remnants of historical extragalactic SNs to be unambiguously detected in the optical (cf. Stringfellow *et al.* 1988; Fesen and Becker 1988). Assuming a mean expansion velocity of 5000 km s^{-1}, the freely expanding shell from the SN would now have a radius of 4×10^{17} cm. A quantitative discussion of the physical characteristics of the nebula is difficult on the basis of a single emission line. However, the detection of the object in [O III] and the weakness of the other lines is significant, making this a new member of the oxygen-rich or ejecta-dominated class of SNRs, confirming the suspicion that SN 1957D had a massive progenitor, and suggesting that the SN was of type II or Ib. The spectrum is not that of a late-time SN in which case a low ionization line like [O I] λ6300 should dominate the high ionization lines of [O III] λλ4959, 5007.

The remnant of SN 1957D clearly merits detailed study in the years to come. Assuming reddening can be neglected, the [O III] luminosity of the remnant of SN 1957D is $\sim 1.5 \times 10^{37}$ ergs s^{-1} or about 3 times that of Cas A. The total amount of oxygen currently emitting optically is not large, $\sim 4 \times 10^{-3}$ $M_\odot$ if physical conditions in the [O III]–emitting knots in this SNR resemble those of Cas A (Peimbert and van den Bergh 1971). But if the emission is due to a reverse shock propagating back into the ejecta, then the SN must already have encountered a substantial amount of circumstellar material. This appears to be consistent with explanations of radio emission in radio SNs which are based upon shocks propagating into the wind of a presupernova star (Chevalier 1982; Weiler *et al.* 1986). For example, for a pre–SN mass-loss rate of 10^{-4} $M_\odot$ yr^{-1}, a wind velocity of 10 km s^{-1} and a mean blast wave velocity of 5000 km s^{-1}, the mass overtaken by the shock would now total 1.5 $M_\odot$. However, most radio SNs fade rapidly with time scales of much less than a year. As a result the connection between SN 1957D and these remnants is not self-evident.

Obviously, detection of X-ray emission from the remnant would greatly constrain models of the SNR. Trinchieri, Fabbiano, and Palumbo (1985) searched for X-ray emission from the sites of historical SNs in M83 but failed to find any with upper limits of 10^{38} ergs s^{-1} which is 50 times the (0.1–4 keV) X-ray luminosity of Cas A. In Cas A (and in the SNR of NGC 4449 [Blair, Kirshner, and Winkler 1983]), the luminosities in [O III] and in (0.1–4 keV) X-rays are comparable. If this is true for the remnant of SN 1957D, then its current X-ray luminosity should be $\sim 1.5 \times 10^{37}$ ergs s^{-1}, well within the reach of the next generation of X-ray telescopes. There are significant differences in the time evolution of the expected flux from a SNR expanding into a medium whose density is falling as r^{-2} (as would be expected if the remnant is expanding into a fossil stellar wind) and from a remnant expanding into a uniform medium. In the first case the mass swept up will double in the next 30 yr; in the second case it will grow by a factor of 8. We note that the [O III] luminosity of the NGC 4449 SNR is some 70 times that of SN 1957D, and its estimated age is ~125 yr (Blair, Kirshner, and Winkler 1983). We expect the time evolution of the remnant of SN 1957D to be a powerful probe of the environment of this object.

Finally, we note that the use of CCDs with interference filters constitutes a powerful new technique for searching for SNRs. The prospects for detection of individual historical SNs depends upon the local environment, the accuracy with which the SN's position is known, the amount of confusion in the field, and the reddening along the line of sight to the object. However, detection of even a few additional objects will lead to a great enhancement of our understanding of SN progenitors and the early stages of remnant development.

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WILLIAM P. BLAIR and KNOX S. LONG: Department of Physics and Astronomy, 170 Rowland Hall, Johns Hopkins University, Baltimore, MD 21218

WOJCIECH KRZEMINSKI: Las Campanas Observatory, Carnegie Institution of Washington, Colina El Pino, La Serena, Chile