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A RAPID DECLINE IN THE OPTICAL EMISSION FROM SN 1957D IN M83

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ABSTRACT

As part of a search for the supernova remnants in M83, we have obtained new interference filter images of the site of SN 1957D and new spectra of the young supernova remnant (SNR) itself. Images were obtained in the light of Hα, [O III], [S II], and several continuum bands using the prime focus CCD camera on the CTIO 4 m telescope. An inspection of the images shows that the flux from the SNR, as observed through the [O III] filter, has decreased by at least a factor of 5 compared with observations made at Las Campanas 4 yr earlier. There is no indication of a change in the emission from the SNR in any other filter. Spectroscopic observations conducted at the position of the SN yield an [O III] flux of 1.8×10^{-15} ergs cm^{-2} s^{-1} in 1991 April, down by a factor of 3 from measurements with the same instrument 2 yr earlier.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernova remnants — supernovae: individual (SN 1957D)

1. INTRODUCTION

SN 1957D is one of six supernovae (SNs) which have been observed in the galaxy M83 (Barbon, Cappellaro, & Turatto 1989).[4] It is located on the inner edge of one of the bright spiral arms of this galaxy away from any bright H II regions. Not a great deal is known about the SN event, which at $m_{pg} = 15$ (Kowal & Sargent 1971) was probably discovered well past optical maximum. There were no published spectra of the SN itself.

SN 1957D was recovered as a nonthermal radio source by Cowan & Branch (1983) some 25 yr after it exploded. Subsequently, Long, Blair, & Krzeminski (1988, 1989; hereafter LBK) and Turatto, Cappellaro, & Danziger (1989; hereafter TCD) recovered optical emission from SN 1957D. The optical spectrum of SN 1957D was dominated by broad [O III] λλ4959, 5007 line emission. These observations confirmed that SN 1957D was the explosion of a massive star, as had been suggested by Pennington, Talbot, & Dufour (1982) on the basis of the integrated colors of the surrounding star field.

Spectroscopically SN 1957D resembles closely the young, oxygen-rich supernova remnants (SNRs), objects which, like SN 1957D, are believed to be the remnants from the demise of massive stars. This class includes Cas A (Chevalier & Kirshner 1979) and G292.0+1.8 (Goss et al. 1979; Murdin & Clark 1979) in the Galaxy, N132D (Lasker 1980) and 0540−69.3 (Mathewson et al. 1980; Kirshner et al. 1989) in the Large Magellanic Cloud, 1E0102−72.3 (Dopita, Tuohy, & Mathewson 1981; Blair et al. 1989) in the Small Magellanic Cloud, and the extraordinarily luminous SNR in the irregular galaxy NGC 4449 (Balick & Heckman 1978; Blair, Kirshner, & Winkler 1983). All these objects have spectra dominated by high-velocity oxygen emission, though some also have fainter lines of neon and/or sulfur. The material responsible for the line emission in SN 1957D, as in the rest of them, must surely be highly processed matter which originated in the core of the progenitor star, and which is still expanding rapidly with little contamination from interstellar or circumstellar material.

Observations of the remnants of historical SNs are important because they probe the circumstellar environment of SNs and provide information on the late evolutionary stages of the progenitor star. A small number of very young (10–100 yr old) SNRs of historical SNs are known to be observable today. These include SN 1961v (Goodrich et al. 1989), SN 1979c (Fesen 1990), SN 1980K (Fesen & Becker 1990; Leibengut et al. 1991), and SN 1957D. However, this number will surely increase as sensitive detectors are used to follow the late-time light curves of more SNs.

In this paper, we describe new optical observations of SN 1957D which show that the optical luminosity of this young SNR is evolving rapidly.

2. OBSERVATIONS AND RESULTS

The imaging observations were made at Cerro Tololo Inter-American Observatory using the 4 m telescope and the prime focus camera with a Tektronix 1024 × 1024 CCD. With this instrumental setup the plate scale is 0".46 pixel^{-1}. The observations, part of a larger search for SNRs in M83, were obtained on 1991 April 18 and 19. Images were obtained through Hα, [S II], [O III], blue, and red continuum filters of three fields

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[4] The sixth SN was only recently recognized on archival plate material and is designated SN 1945B; see IAU Cir. 5091.

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TABLE 1

INTERFERENCE FILTER/CCD IMAGERY OF SN 1957D

Filter	λ_c (1991) (Å)	FWHM (1991) (Å)	Exposure (1991)[a] (s)	λ_c (1987) (Å)	FWHM (1987) (Å)
[O III] …………	5020	54	1800	5028	53
Blue……………	5125	44	1500	…	…
Hα[b] ……………	6560	52	1800	6575	52
[S II] ……………	6719	50	1800	6737	57
Red ……………	6826	85	1200	…	…

[a] Exposure times are listed for a single field—the field which was centered on the nucleus of M83. There are comparable exposure times for the NW field which also included SN 1957D.

[b] The Hα filters also pass significant amounts of [N II] λλ6548, 6581.

in M83, two of which included SN 1957D. The filters, their characteristics, and the exposures through each filter are listed in Table 1. The characteristics for the filters used in the 1987 observations from Las Campanas (LBK) are also shown. Similar but not exactly identical filters were used to isolate emission lines in both runs. At CTIO the filters are located in the f/2.8 converging beam, while at Las Campanas they were used in an f/7.5 beam. Thus the pass bands for the two sets of observations are slightly different. The filters have been recalibrated several times over the past few years, and no significant changes have been noted.

Three subexposures were taken at each position and then combined to reduce the effects of cosmic rays. Data reduction, which consisted of bias subtraction, trimming, flat-fielding (using both dome flats and sky flats), and then combining subexposures, was accomplished using standard IRAF[5] techniques. Flux calibrations based on standard stars (Stone & Baldwin 1983) were consistent within 10% from night to night. The seeing, as measured in the reduced and combined images, was somewhat better on 18 April (1″.5) than on 19 April (1″.7).

In our 1987 imagery of M83 (LBK), SN 1957D was identified as a nebula, located at the site of the historical SN, which was bright in [O III] but weak or absent in Hα, [O I], and continuum images. A 40″ portion of M83, centered on the site of SN 1957D, is shown in Figure 1 (Plate 11) as observed through (*a*) the blue continuum filter in 1991, (*b*) the Hα (+[N II]) filter in 1991, (*c*) the [O III] filter in 1987, and (*d*) the [O III] filter in 1991. Insofar as is possible, we have attempted to scale the images so that stars of equal brightness have the same appearance in each image. The 1987 [O III] image has been convolved with a Gaussian to match the point-spread function of the 1991 [O III] image. Most features in the two [O III] images, including H II regions, have the same appearance in 1987 and in 1991, with the exception of SN 1957D which is clearly much fainter in 1991.

To estimate the total flux from SN 1957D in 1991, we have scaled and subtracted an aligned portion of the blue continuum image from the [O III] image. The excess flux in the continuum-subtracted [O III] image in a circular aperture 5 pixels (2″.3) in radius is $\sim 2.4 \times 10^{-15}$ ergs cm^{-2} s^{-1}.

To cross-calibrate our 1987 and 1991 images we used IRAF's "qphot" procedure to carry out aperture photometry of 20 stars in the vicinity of SN 1957D in both sets of data and thereby derive the relative sensitivity of the two observations. On the basis of this approach, we estimate that SN 1957D was 5.1 times brighter in [O III] in 1987, with a flux of 1.2×10^{-14} ergs cm^{-2} s^{-1}. (This number should be preferred, at least for the purpose of a relative comparison, to the value of 2×10^{-14} ergs cm^{-2} s^{-1} which LBK estimated from the 1987 images using a calibration based on standard stars.)

Since the discussion of LBK, we have obtained two sets of spectra of SN 1957D, both from the CTIO 4 m telescope with the R-C spectrograph and blue air-Schmidt camera. The first set of observations was carried out 1989 February 14 and 15, with GEC no. 11 CCD as the detector. Grating 250 was used, which covered the range 3600–6850 Å, with a dispersion of 5.7 Å pixel^{-1} and a resolution of 15 Å (FWHM). The second set of observations was carried out 1991 April 22, a few days after the imagery described above. For these spectra the instrumental setup was similar to that in 1989, except that we used grating KPGL2 and the newly available Reticon 400 × 1200 CCD, to give 3200–7550 Å coverage with a dispersion of 3.6 Å pixel^{-1} and a resolution of 10 Å. A journal of the observations is given in Table 2.

Both sets of spectra were reduced using identical IRAF procedures for bias subtraction, flat-fielding, wavelength calibration, and distortion correction. Background subtraction was accomplished in two stages. First, the entire two-dimensional spectrum was background-subtracted (line-by-line) prior to making wavelength and distortion corrections, in order to remove night-sky emission that was relatively constant along the slit. Since there is rapidly varying diffuse H II emission in the vicinity of SN 1957D, a second background subtraction was carried out using several columns adjacent to the object, in order to remove as much as possible of the contamination from nearby emission. All of the two-dimensional spectra were flux-calibrated using observations of several Stone & Baldwin (1983) flux standards, and one-dimensional spectra of SN 1957D were extracted. Finally, all the extracted spectra from each year were combined to give the results shown in Figure 2.

In the 1989 spectrum there are broad emission features at [O II] λλ3727, 3729, [O III] λλ4959, 5007, and probably at [O I] λλ6300, 6363. In addition, there are also narrow emission

TABLE 2

CTIO 4 m SPECTROSCOPIC OBSERVATIONS OF SN 1957D

Date (GMT)	Integration time (s)	λ_{min} (Å)	λ_{max} (Å)	Resolution (FWHM) (Å)
1989 Feb 14………	1500	3600	6850	15
1989 Feb 15………	1000	3600	6850	15
1991 Apr 22………	4000	3200	7550	10

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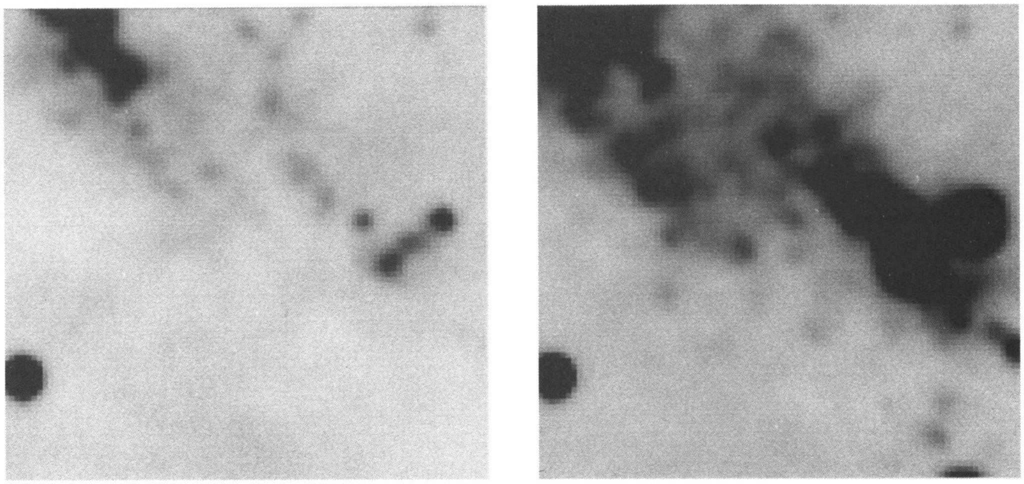
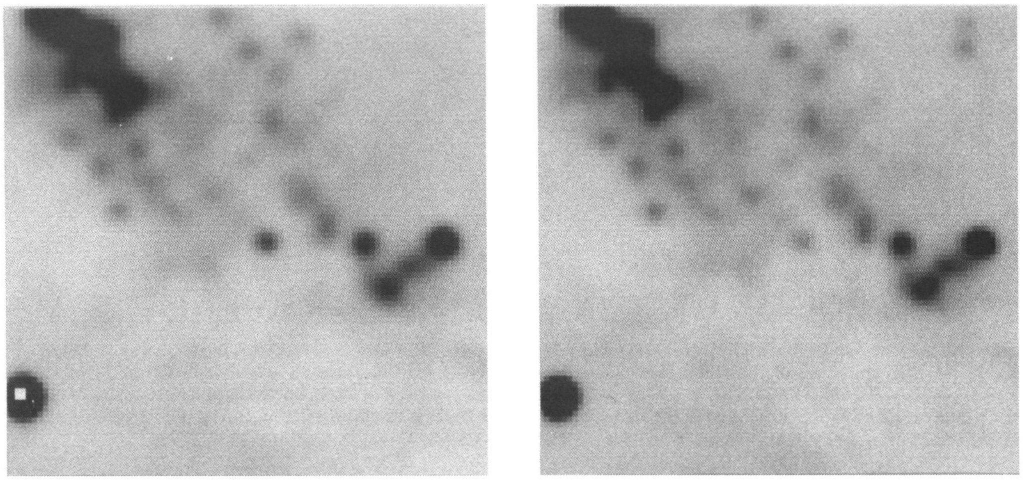
[5] The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories operated by the Association for Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.



a) 6100 b) Hα



c) [0III]-1987 d) [0III]-1991

FIG. 1.—Images of the site of SN 1957D as observed through (*a*) the blue continuum filter in 1991, (*b*) the Hα filter in 1991, (*c*) the [O III] filter in 1987, and (*d*) the [O III] filter in 1991. The original 1987 [O III] image was obtained in better seeing conditions than any of the new CTIO images. To facilitate comparison the 1987 image was convolved with a Gaussian to produce an image with the same effective resolution as the new [O III] image. The images have been displayed so that objects of equal brightness appear with equal intensity in all of the images. The size of the field shown is ~40″. North is up, and east is to the left in the figure. That SN 1957D has faded in [O III] is readily apparent from comparison images obtained in the two epochs. There is a faint but discernible H II region coincident with the site of SN 1957D in the Hα image.

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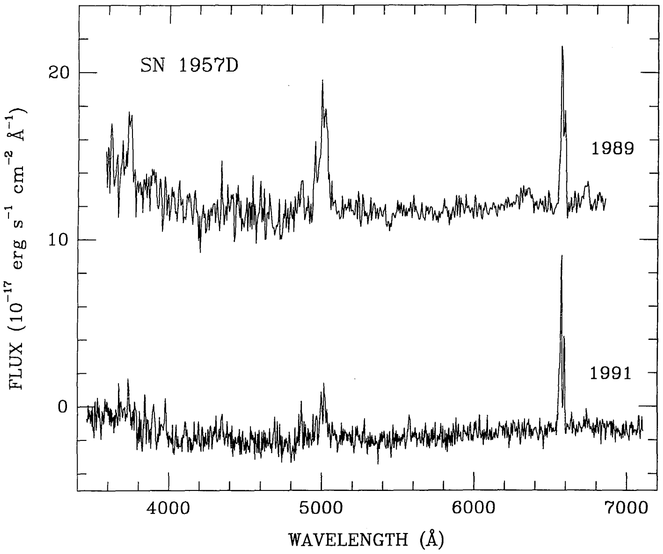

FIG. 2.—Spectra of SN 1957D obtained in 1989 February and 1991 April with the CTIO 4 m telescope.

lines due to Hα, Hβ, [N II] λλ6548, 6583, and [S II] λλ6717, 6731. All the broad lines are much fainter in the 1991 spectrum, where [O III] is the only broad feature that can be positively identified. The narrow-line features are similar in both spectra and are likely due to H II region emission that is along the line of sight to SN 1957D; whether or not this emission is physically associated with the remnant is unclear. Line fluxes and widths obtained by fitting Gaussian profiles are listed in Table 3.

The one-dimensional spectra of both 1989 and 1991 were extracted by summing only the three columns of the CCD chip with the highest signal-to-noise ratio (S/N). This represents a spatial extent of only 2″.2 and 2″.6 in 1989 and 1991, respectively, too small to capture the full flux from an unresolved source. To correct for this effect, we examined the profiles of standard stars observed before and after the SN 1957D observations, comparing the flux in three columns centered on the stars with that in the wider apertures used for flux calibration. The result is that the SN 1957D fluxes should be multiplied by a factor of 1.18 (1989) or 1.50 (1991). We have already applied these correction factors to obtain the line fluxes reported in Table 3. We estimate an Hα:Hβ ratio of 3.6 for the faint H II emission coincident with SN 1957D. Measurements for the much brighter H II regions located 7″ and 12″ to the west give values of 3.5 and 3.2, respectively. These values suggest that the reddening to SN 1957D is modest, $E(B-V) \approx 0.06$–0.17, assuming an intrinsic ratio of 3.0. We have not corrected the flux values in Table 3 for reddening.

LBK reported a velocity width of 2600 km s^{-1} (FWHM) for each component of [O III]. We measure 2900 km s^{-1} for these lines in our 1989 spectrum and 2500 km s^{-1} in 1991. We also measure a width of 2400 km s^{-1} for the [O II] lines in 1989. There is no obvious trend, and, due to the faintness of SN 1957D, we do not believe these small differences constitute any real evidence for a change in the line widths. The central velocity for the [O III] lines, also obtained from fitting Gaussian profiles, is ~350 km s^{-1} in both 1989 and 1991. This is not significantly different from the redshift of 390 km s^{-1} for the narrow lines which we believe arise from the faint H II region coincident with SN 1957D.

TCD reported a spectrum of SN 1957D taken in April 1989, 2 months after our 1989 observations. The two spectra are qualitatively very similar, but theirs represents an exposure 3 times longer and has higher S/N, while ours extends farther to the blue. TCD measured a flux of $\sim 2 \times 10^{-15}$ ergs cm^{-2} s^{-1} for the [O III] lines, a factor of 2.5 lower than what we measured 2 months earlier. In view of the high S/N of their spectrum which was also obtained on a 4 m class telescope and its similarity to ours in relative line strengths and profiles, we wonder whether their spectrum has been accurately flux-calibrated. If all the flux calibrations are correct, the drop in SN 1957D's flux must have been precipitous, occurring between 1989 February and April! TCD also reported that the [O III] lines are asymmetric, with a velocity of maximum emission blueshifted by about 650 km s^{-1} relative to the rest frame of M83. Our 1989 line profiles are consistent with such an asymmetry, but the S/N of our spectrum is not high enough to make a case for other than Gaussian profiles.

As summarized in Table 4, the evidence that the [O III] flux from SN 1957D has faded over the past 4 yr, by roughly a factor of 5, is convincing. Intervening data between 1987 and 1991 are all from spectra with limited S/Ns, but (with the exception of the TCD result) these data are consistent with uniform fading over time. There is no evidence for any change in the width of the [O III] lines, despite the fact that their strength has declined. Furthermore, the data are consistent with similar declines in flux for lines from [O III], [O II], and [O I]. In particular, there has been no increase in the flux from low-ionization species of oxygen to compensate for the decline in [O III] emission.

3. DISCUSSION

The optical spectrum from SN 1957D is dominated by lines of oxygen with velocities in excess of ±2000 km s^{-1}. Since only narrow lines of hydrogen are observed, these cannot stem from the fast-moving regions and likely are unrelated to SN 1957D. As noted previously, spectroscopically SN 1957D

TABLE 3

OBSERVED FLUXES AND LINE WIDTHS FOR SN 1957D

Ion	Wavelength (Å)	1989 Observed Flux[a]	1989 FWHM (Å)	1991 Observed Flux[a]	1991 FWHM (Å)
[O II]	3726, 3729	1.5	28	...	...
[O III]	4959	1.4	48	0.3	43
[O III]	5007	3.9	48	1.5	43
[O I]	6300+6363	0.9	...	...	...

[a] In units of 10^{-15} ergs cm^{-2} s^{-1}.

TABLE 4

HISTORY OF REPORTED [O III] FLUXES

Date of Observation	Flux[a]	Method	Source
1987 Apr	12.0	Images	LBK
1988 Aug	5.0	Spectra	LBK
1989 Feb	5.3	Spectra	This paper
1989 Apr	2.0	Spectra	TCD
1991 Apr	2.4	Images	This paper
1991 Apr	1.8	Spectra	This paper

[a] In units of 10^{-15} ergs cm^{-2} s^{-1}.

resembles closely the young, oxygen-rich SNRs such as Cas A. What is unique about SN 1957D is the short time scale over which its total luminosity has changed drastically. In Cas A, individual knots have been observed to appear and/or dissipate on time scales of a few years (van den Bergh & Kamper 1985), but none of these has had any substantial effect on the overall luminosity of Cas A. The changes we have observed in SN 1957D—a luminosity decrease by a factor of 3–5 with no apparent change in the velocity distribution of the emitting material—can hardly be attributed to the disappearance of one or a few individual knots. Instead it is much more plausible that something has caused the entire assemblage of emitting material to decrease in brightness. Furthermore, the drop cannot be attributed simply to a rapid cooling of high-density material following the passage of a shock, for in that case we would expect the drop in [O III] emission to be accompanied by a rise in that from [O II] and/or [O I], which is not observed.

Very few SNRs with ages of 10–50 yr have been detected optically. There is not enough data on any of these SNRs to know whether the behavior of SN 1957D is unusual. More SNRs have been monitored at radio wavelengths. Radio emission is commonly observed from Type II SNs in relatively nearby galaxies. In most cases the emission peaks in the first year after the SN explosion and fades with a decay rate of $t^{-0.6}$ to $t^{-0.8}$ (Weiler et al. 1986; Weiler et al. 1991).[6] The fact that all of the optically observed 10–50 yr old SNRs are also known as radio sources suggests a connection between the radio and optical emission mechanisms. But if SN 1957D is decaying as $t^{-0.7}$ then it would have decayed only by ~8% in 4 yr.

Two models have been developed to explain the time evolution of the radio emission. The model which is generally preferred involves the interaction of the SN blast wave with the circumstellar medium (CSM) of the pre-SN star (Chevalier 1982). This model accounts naturally for the fact that the radio emission peaks first at higher frequencies and predicts a late time decay rate of $t^{-0.7}$ for a blast wave expanding into a CSM in which the density scales approximately as r^{-2}. In Chevalier's model, only a small fraction (1%) of the energy released as the SN blast wave propagates into the CSM and, as a reverse shock is driven back into the ejecta, goes into creating magnetic fields and relativistic radiation. The bulk of the energy goes into the postshock gas in the ejecta and the CSM. Substantial X-ray emission should be produced—hard X-rays from the 10^9 K plasma immediately behind the shock front and even more soft X-rays from the 10^7 K plasma as a reverse shock is driven into the ejecta.[7]

Optical emission is an inherent feature of this model because half of the X-ray flux will be directed inward where it will photoionize unshocked ejecta which will then radiate strongly in lines such as [O III] $\lambda\lambda$4959, 5007. A sudden drop in the density of the CSM provides a natural mechanism for turning off the optical emission. A drop in density causes a drop in the postshock pressure which slows the reverse shock and reduces the X-ray luminosity; this in turn causes a rapid decline in the emission-line luminosity.[8] Assuming a mean expansion rate of 10,000 km s^{-1}, then the blast wave in SN 1957D is now at a radius of $\sim 10^{18}$ cm. Weiler et al. (1989) assume a pre–SN wind velocity of ~10 km s^{-1} and estimate a mass loss rate of 2×10^{-5} $M_\odot$ yr^{-1} for the progenitor of SN 1957D, such as may occur during the red supergiant phase of stars with main-sequence masses in the range of 7–15 $M_\odot$. If this is correct, then the duration of the high mass-loss phase of the supergiant wind must have been of order 3×10^4 yr and the total amount of matter carried away in the wind must have been $\sim 0.6 M_\odot$.

We do not know whether the radio luminosity of SN 1957D has evolved like that of typical radio SNs. It is equally probable that a concentration of CSM in one or more shells, as has been observed in SN 1987A (Jakobsen et al. 1991; Panagia et al. 1991), could provide the trigger for varying emission as the blast wave first encounters, and then breaks out of the circumstellar shell. Luo & McCray (1991) have modeled the interaction of the primary shock with the shell in SN 1987A, and they predict that its radio and optical luminosity will reach that of SN 1957D ~ 15 yr after the explosion.

While we believe a model similar to that described above is most likely to be correct, it is not possible to rule out completely the possibility that the radio and optical emission in SN 1957D is produced by a synchrotron nebula powered by a rapidly spinning pulsar (Pacini & Salvati 1973; Bandiera, Pacini, & Salvati 1984). Weiler et al. (1986) have shown that, with a suitable choice of parameters, the radio luminosity of a pulsar-powered nebula can evolve to match the observed light-curves of young SNRs. In the Crab Nebula, which is about 30 times older than SN 1957D, a powerful pulsar does power the evolution, and the observed filaments are heated primarily by photoionization due to 10–1000 eV synchrotron photons. [O III] λ5007 is the brightest optical line in many filaments, even though the abundance of oxygen is thought to be no more than solar (Fesen & Kirshner 1982; Henry & McAlpine 1982). The main argument against this explanation for the radio emission in young SNs has been that the radio emission is difficult to get out of the nebula unless nearly all of the ejecta have collapsed into filaments. However, Bandeira, Pacini, & Salvati (1983) have argued that various instabilities, including Rayleigh-Taylor instabilities caused by the interaction of the pulsar wind and synchrotron nebula with the ejecta, could lead to early filamentation in Type II SNs. And there is increasingly strong evidence for clumping of various ions in the ejecta of SN 1987A and SN 1988A, two Type II events, within a few years of the explosion (Mosely et al. 1989; Spiromilio, Meikle, & Allen 1990; Spiromilio 1991). The argument that the radiation cannot escape is most compelling in very young SNs observed within a year or two of their explosion. In SN 1957D which was not studied as a radio source until nearly 25 yr after its explosion, there will have been a greater length of time for filamentation to complete. But there is no obvious explanation for a rapid decline in the optical flux after 30 yr if an expanding synchrotron nebula is responsible for the emission we see, especially since the optical emission should penetrate the plasma in the ejecta better than the radio emission. However, Woosley, Pinto, & Hartman (1989) have suggested that the behavior of a young pulsar in a SNR may be more like that of an X-ray

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[6] SN 1970G is an exception to this rule. Its radio flux decayed by a factor of about 30 between observations in 1974 and 1990 (Cowan, Goss, & Sramek 1991). This corresponds to decay rate of $t^{-1.95}$. Unfortunately there were no radio observations of SN 1970G between 1974 and 1990.

[7] The only SNs which have been detected at X-ray wavelengths are SN 1980K (Canizares, Kriss, & Feigelson 1982) and SN 1987A (Sunyaev et al. 1987; Dotani et al. 1987) which is a comment more on the sensitivity of X-ray observations than on the correctness of the model.

[8] Photoionization models for young SNRs suggest effective temperatures of order 20,000 K and total emissivities for oxygen of $\geq 10^{-21}$ ergs cm^3 s^{-1} (Dopita 1987; Blair et al. 1989). This implies a cooling time scale of order 1 yr if the density is 100 cm^{-3}. Since the densities are likely to be much greater than this, the optical emission lines should track the X-ray luminosity.

pulsator than that of the pulsar in the Crab Nebula. Our meager measurements certainly do not constrain these and other more exotic models.

On the other hand, the detection of rapid variability in the flux from SN 1957D makes it very unlikely that the optical emission in SN 1957D is due to gas photoionized by the radioactive decay of nuclei with long half-lives (^{57}Co or ^{44}Ti; Woosley et al. 1989). Fesen & Becker (1990) have suggested that optical emission in SN 1980K is powered by this mechanism, although they point out that much more ^{44}Ti would have to have been produced than models for the SN 1987A explosion predict.

In conclusion, the discovery of a rapid decline in the optical luminosity of SN 1957D makes it blatantly clear that it is worthwhile to monitor the fluxes at all wavelengths of old SNs as they become young SNRs. Such objects enable us to probe the close environment of the progenitors of SNs. In the context of models of very young SNRs which involve the interaction of SN blast waves and the CSM, the rapid decline in the [O III] luminosity that we observe can be understood in terms of a sudden drop in the density of that medium at the present radius 1×10^{18} cm of the blast wave.

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