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THE OPTICAL COUNTERPART TO THE LUMINOUS X-RAY SUPERNOVA REMNANT IN NGC 6946

William P. Blair[1]
Department of Physics and Astronomy, The Johns Hopkins University, 34th and Charles Streets, Baltimore, MD 21218
and
Robert A. Fesen
Department of Physics and Astronomy, 6127 Wilder Lab, Dartmouth College, Hanover, NH 03755
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ABSTRACT

We identify a high surface brightness optical supernova remnant (SNR) in NGC 6946 that is coincident with a bright soft X-ray point source detected in a *ROSAT* PSPC image of this galaxy (Schlegel 1994). Optical CCD/interference filter images and spectra show the object to have an observed Hα flux of 1.9×10^{-14} ergs cm^{-2} s^{-1}, corresponding to an intrinsic Hα luminosity of 2×10^{38} $(d/5.1 \text{ Mpc})^2$ ergs s^{-1}. A moderate-resolution optical spectrum shows normal SNR line emissions, with no high velocities ($V < 400$ km s^{-1}) or relative line strengths indicative of enriched heavy element abundances. This suggests a relatively old SNR, a conclusion supported by the presence of an emission nebula at its position on photographic plates dating back to at least 1921. With both an optical line flux and soft X-ray flux exceeding those of other luminous extragalactic SNRs, this object may have an optical luminosity near the maximum limit for SNRs. Assuming current flux levels, we estimate the SNR's age to be $\lesssim 3500$ yr and suggest its unusual luminosity is due to both its expansion into dense surroundings and a relatively low column density along our line of sight.

Subject headings: galaxies: individual (NGC 6946) — ISM: supernova remnants

1. INTRODUCTION

The face-on spiral galaxy NGC 6946 (SAB(rs)cd, de Vaucouleurs, de Vaucouleurs, & Corwin 1976; $d = 5.1$ Mpc, de Vaucouleurs 1979) has shown an unusually high supernova rate, generating at least six supernovae (SNe) in the last 75 years. This rate is rivaled only by M83, also a face-on Scd galaxy, which has had six recorded SNe (cf. Cowan & Branch 1985 and references therein; also IAU Circ., No. 5091). Both of these galaxies show evidence of active star formation and starburst activity, with many of the observed SNe expected to arise from massive young stars. With so many historical SNe seen, a large number of young supernova remnants (SNRs), perhaps older than the historically observed SNe but still young by SNR standards, might be present in these galaxies. Some of these remnants might even be expected to be in the "ejecta-dominated" phase such as the young SNR in NGC 4449 (Blair, Kirshner, & Winkler 1983). These considerations motivated us to perform CCD/interference filter surveys of these galaxies to search systematically for optical SNR candidates.

As part of a SNR survey of NGC 6946, we have discovered an extraordinarily bright SNR that has escaped recognition to date. This object lies within the error circle of a bright pointlike *ROSAT* PSPC source in NGC 6946 identified by Schlegel (1994). In this *Letter* we report optical images and spectroscopy of this object that confirm the SNR identification. Our findings indicate this object to be an unusually luminous but otherwise normal interstellar medium–dominated SNR. It is not a young, ejecta-dominated remnant as its X-ray luminosity might at first suggest. Our observations are described in § 2, while we discuss the results in § 3 and compare our optical data with data from other spectral regions.

2. OBSERVATIONS AND REDUCTIONS

2.1. *Optical Imaging*

Optical CCD images of NGC 6946 were obtained on 1990 September 28 at Kitt Peak National Observatory. These were obtained using a Tektronics 2048 × 2048 CCD at the prime focus of the 4 m Mayall telescope. Interference filters and exposure times used were as follows: an Hα filter ($\lambda_0 = 6571$ Å, FWHM = 34 Å; 1500 s), a [S II] filter ($\lambda_0 = 6735$ Å, FWHM = 51 Å; 2300 s), a red continuum filter ($\lambda_0 = 6105$ Å, FWHM = 145 Å; 1200 s), and an [O III] filter ($\lambda_0 = 5027$ Å, FWHM = 53 Å; 2400 s). The redshifted centroid of the Hα filter combined with the low observed radial velocity of NGC 6946 (46 km s^{-1}; de Vaucouleurs et al. 1976) means that [N II] λ6584 is also passed by the Hα filter at a significant level; however, for simplicity we will refer to this as the Hα filter exposure. With 0".53 pixels, stars in the image have FWHM ~1".4. The sky transparency during the imaging was excellent. The images were reduced using standard techniques from within the IRAF[2] package. Images were bias subtracted, flat-field corrected using normalized dome flat fields, and cleaned of cosmic rays using the "imedit" task in IRAF. Spectrophotometric standard stars were observed through the Hα, [S II], and 6100 Å filters and observed count rates converted into fluxes. No photometric standard was obtained for the [O III] filter. The full frame data and SNR survey of this galaxy will be reported elsewhere.

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Strong [S II] emission with respect to Hα has been a criterion used successfully in surveys of nearby galaxies for distinguishing shock-heated nebulae from photoionized regions (Long et al. 1990, and references therein). In Figure 1 (Plate L8), we show a collage of the images for the 1'.3 region around the X-ray source position (Schlegel 1994). A candidate SNR can be seen in the emission line images, with strong [S II] and [O III] emission in comparison with H II regions of about the same Hα brightness, and no significant contamination by underlying continuum. The SNR candidate's optical position was determined using the positions of *HST* guide stars on the original full-frame CCD data to provide a frame of reference. From this analysis, we determine a J2000 coordinate of R.A. = $20^h35^m00^s.6$, Decl. = +60°11'30". Positions obtained in this way are usually accurate to better than 2". This position does not correspond to any of the known historical SNe in NGC 6946 (Barbon, Cappellaro, & Turatto 1989). However, it is within the error circle of the *ROSAT* PSPC source identified by Schlegel (1994), and it coincides within errors with a faint radio point source (Van Dyk et al. 1994).

Although the images indicate the emission-line object coincident with the X-ray source is likely to be a SNR, they cannot help determine its type or age. Elevated [O III] emission relative to Hα in SNRs can indicate shock velocities $\gtrsim 100$ km s^{-1} while extreme [O III]:Hα ratios (≥ 15) are often seen in young ejecta-rich SNRs (e.g., Cas A: Chevalier & Kirshner 1979; NGC 4449 SNR: Blair et al. 1983) where the optical spectrum is dominated by [O I], [O II], and [O III] lines. However, the relative strength of [O III] emission can be diminished in such a remnant if it is embedded within an H II region. Therefore, spectroscopy is needed to confirm the identification and determine which type of SNR it is.

2.2. *Optical Spectroscopy*

A moderate-resolution spectrum was obtained on 1993 June 18 (UT) using the 2.4 m Hiltner telescope at the Michigan-Dartmouth-MIT Observatory situated on the southwest ridge of Kitt Peak, Arizona. A 300 l mm^{-1} 5400 Å blaze grism was used on the MK III spectrograph with a 2048 × 2048 Loral CCD detector. A long slit with width 1".7 oriented N-S yielded an effective resolution of 8 Å and spectral coverage from 4700 to 7500 Å. A single 900 s exposure was obtained at the position of the suspected SNR. This was reduced using standard IRAF software routines, Ne-Hg calibration lamp exposures, and an observation of the flux standard HD 161817. Cosmic rays were removed manually in the final reduction. The emission corresponding to the SNR was extracted into the one-dimensional spectrum shown in Figure 2. The radial velocity calibration is accurate to ±75 km s^{-1} and absolute flux caibration should be accurate to ±25%, limited mainly by possible light loss due to the narrow slit. Relative line intensities, especially for the bright lines, should be accurate to better than 15%.

Line intensities were measured using the "splot" task in IRAF. The observed fluxes are listed in Table 1, along with line identifications. The observed line intensities have been corrected for reddening assuming a Savage & Mathis (1979) galactic curve and an assumed intrinsic ratio of Hα:Hβ = 3.0. The reddening correction applied corresponds to $E(B-V) = 0.52$. This is larger than the value of 0.40 estimated for NGC 6946 by Burstein & Heiles (1982), but smaller than the value of 0.60 one derives using the best N(H) fit from the *ROSAT* X-ray data (Schlegel 1994) and applying Bohlin, Savage, & Drake's (1978) standard ratio of $N(\mathrm{H})/E(B-V) = 5.8 \times 10^{21}$ cm^{-2} mag^{-1}.

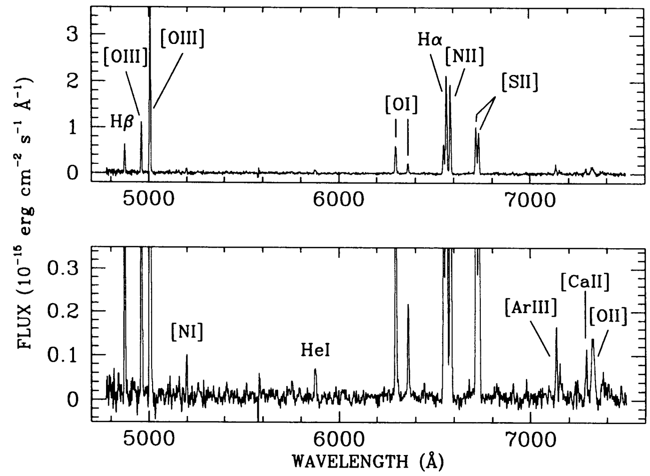

FIG. 2.—Medium-resolution optical spectrum of the SNR. Top panel shows the strong lines and the bottom panel shows the fainter lines. Line identifications are cross referenced to Table 1.

For convenience, we list both the observed (F) and reddening corrected (I) line intensities in the table scaled to Hβ = 100.

3. ANALYSIS AND DISCUSSION

The optical emission line source we identify near the reported X-ray position (Schlegel 1994) possesses several optical properties of a SNR. It shows strong [S II] with a [S II]:Hα ratio of 0.85 which is well above the 0.4 threshold value commonly used to identify shock heated nebulae (cf. Long et al. 1990). In addition, secondary indicators of shock heating, including the presence of strong [O I] emission and elevated [N II] and/or [O III] with respect to the Balmer lines, are all consistent with a shock heated nebula. These line emission properties, together with a large X-ray flux, strongly argue for a SNR classification.

However, contrary to expectations based on its high X-ray flux, the object's optical spectrum reveals no evidence for either

TABLE 1

OBSERVED AND INTRINSIC LINE INTENSITIES FOR THE SNR IN NGC 6946

λ (Å)	Line ID	F_{obs} [a]	F(Hβ = 100)	I(Hβ = 100)[b]
4861	Hβ	3.5E−15	100	100
4959	[O III]	7.6E−15	220	210
5007	[O III]	2.5E−14	715	670
5199	[N I]	7.0E−16	20	18
5876	He I	7.0E−16	20	15
6300	[O I]	4.9E−15	140	85
6364	[O I]	1.6E−15	45	27
6548	[N II]	5.5E−15	160	90
6563	Hα	1.9E−14	540	300
6583	[N II]	1.6E−14	460	255
6678	He I	1.8E−16	5	3
6717	[S II]	9.0E−15	260	140
6731	[S II]	7.5E−15	215	115
7135	[Ar III]	1.3E−15	40	18
7155	[Fe II]	3.4E−16	10	5
7291	[Ca II]	6.7E−16	20	9
7324	[Ca II] + [O II]	2.1E−15	60	28

[a] Observed fluxes are given in units of ergs cm^{-2} s^{-1}.

[b] Reddening correction assumes $E(B-V) = 0.52$ and a standard galactic extinction curve (Savage & Mathis 1979). For scaling, the reddening corrected Hβ flux is 2.0E−14 ergs cm^{-2} s^{-1}.

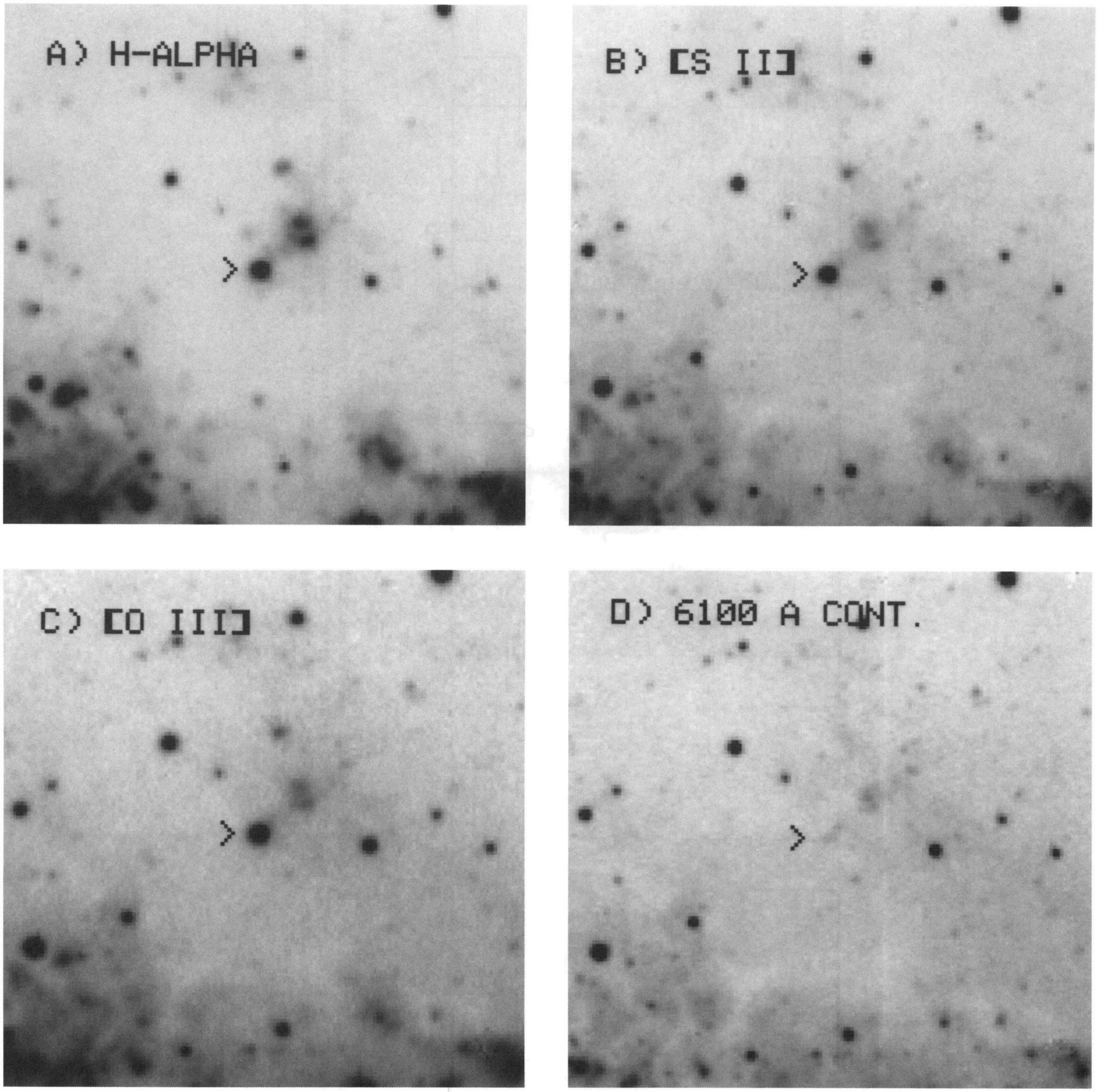

FIG. 1.—CCD interference filter images of a portion of NGC 6946 showing the optical SNR which is coincident with the bright X-ray source identified by Schlegel (1994). (*a*) Hα; (*b*) [S II]; (*c*) [O III]; (*d*) 6100 Å continuum. North is up, and east is to the left. The region shown is 1'.35 on a side. The fainter nebula $\sim$25" NW of the SNR may also be a supernova remnant.

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a young age or heavy-element enrichment like that seen in remnants of massive stars (cf. Blair, Kirshner, & Winkler 1983; Dopita & Tuohy 1984; Kirshner et al. 1989). In fact, the spectrum looks qualitatively similar to that commonly seen in evolved galactic and extragalactic SNRs (Blair, Kirshner, & Chevalier 1982; Fesen et al. 1985; Blair & Kirshner 1985). The 8 Å resolution of our spectrum permits us to place a limit of only $\lesssim$400 km s^{-1} on any high velocity material. Although this is not particularly restrictive, we find no evidence in any line profiles for high expansion velocities that would indicate a young SNR such as Cas A (4000–12,000 km s^{-1}; Fesen, Becker, & Goodrich 1988), N132D in the LMC (2250 km s^{-1}; Lasker 1980), SN 1957d in M83 (2500 km s^{-1}; Long, Blair, & Krzeminski 1989), or the luminous, young SNR in NGC 4449 (3500 km s^{-1}; Blair, Kirshner, & Winkler 1983).

There is also no evidence to indicate that this emission nebula has changed significantly in brightness over the last 70 to 90 years. The object we identify as a SNR was cataloged as an H II region (No. 237) by Bonnarel, Boulsteix, & Marcelin (1986). The object can be seen at about this same brightness on a photograph of NGC 6946 taken on 1921 June 19/20 by M. Humason (see plate XII in Hubble 1936) and is also probably detected on an 1899 August 7 plate taken by Keeler (1908, plate 62). Based on kinematics, spectral characteristics, and archival observations, we conclude that this SNR is considerably older than the six historically observed SNe in NGC 6946.

The object's line fluxes have been determined from both the image and spectral data. For [S II], we obtain $F = 1.67 \times 10^{-14}$ ergs cm^{-2} s^{-1} from the image, and $F = 1.65 \times 10^{-14}$ ergs cm^{-2} s^{-1} from the spectrum (for both lines of the doublet). For Hα, we find $F = 2.65 \times 10^{-14}$ ergs cm^{-2} s^{-1} from our image, and $F = 1.9 \times 10^{-14}$ ergs cm^{-2} s^{-1} from the spectrum. This is consistent with some contamination of the "Hα" image by the strong [N II] λ6584 line from the SNR, as expected from the filter width. The Hα flux derived from our spectrum is a factor of ~6 below Bonnarel et al.'s (1986) measured Hα flux of 1.16×10^{-13} ergs cm^{-2} s^{-1} based on photographic data using a 25 Å (FWHM) filter centered at 6558 Å (hence, very little [N II] contamination expected). The reason for this flux discrepancy is not understood. However, we note that Bonnarel et al. list the size of the nebula to be 4″, which would mean that our 1″.7 slit could have missed some emission. On the other hand, our images show the nebula to be marginally resolved. From our [S II] image, which had the best effective seeing (average FWHM of stars = 1″.26), the SNR has FWHM = 1″.61. Deconvolving this implies an actual diameter of 1″.0, which corresponds to a linear diameter of ~25 pc at 5.1 Mpc. The agreement between the fluxes estimated from our separately calibrated images and spectroscopy also argues against a significant underestimate of the fluxes from the spectra.

The SNR's relative line intensities (Table 1) can be compared to published shock model calculations such as those of Dopita et al. (1984), Cox & Raymond (1985), and Hartigan, Raymond, & Hartmann (1987). The only thing unusual about the object's relative line intensities is the strength of the [O III] lines with respect to Hβ. In steady flow shock models with cosmic abundances, the [O III] lines "turn on" as the shock velocity increases above ~100 km s^{-1}, but never get above a ratio of λ5007:Hβ ~ 4.5. The observed ratio of 6.7 is ~50% above this. This could be indicating the presence of incomplete shocks (i.e., shocks missing the cooler parts of the recombination and cooling zone), as has been seen at some positions in the Cygnus Loop and other SNRs (cf. Hester, Parker, & Dufour 1983; Fesen, Blair, & Kirshner 1985, and references therein). This situation is thought to arise from a recent encounter between a shock and a cloud, where the full postshock flow has not had time to be established. Hence, this might mean we are viewing the object shortly after the blast wave has encountered a density enhancement (e.g., a molecular cloud or a cavity wall). Alternatively, if the ISM abundances in this region of NGC 6946 were well below solar, the [O III] lines could carry a greater fraction of the cooling and therefore be enhanced. While the SNR does lie along the edge of an outlying spiral arm where heavy element abundances are expected to be lower, spectral data on H II regions in NGC 6946 (McCall 1982) indicate little global difference in oxygen abundance between the Galaxy and NGC 6946 (Tosi & Diaz 1985).

The remnant's [S II] λλ6716, 6731 lines can be used as electron density diagnostics in the S^+ region of the postshock flow and they show a typical, evolved SNR density value. Using the formulation of Blair & Kirshner (1985), we find $n_e = 160^{+80}_{-90}$ cm^{-3}, assuming $T = 10^4$ K for the S^+ zone and a 10% error in the ratio. Steady flow models near 100 km s^{-1} indicate a compression of ~45 relative to preshock conditions at this point in the flow, so preshock densities of ~1–5 cm^{-3} are indicated. This assumes, however, that compression is not limited by magnetic fields or other effects, which may not be the case (cf. Raymond et al. 1988). Hence the actual preshock density could be considerably higher.

What is remarkable about this SNR is its high luminosity. Using the reddening corrected line intensities from Table 1 and an assumed distance of 5.1 Mpc, we list in Table 2 the SNR's intrinsic luminosities for several optical lines. For comparison we also tabulate values for N49, the highest optical surface brightness SNR in the LMC (see Vancura et al. 1992) and the luminous young SNR in the irregular galaxy NGC 4449 (Blair, Kirshner, & Winkler 1983). From Table 2, one can see that the NGC 6946 SNR is some 6–30 times brighter than N49 in the key optical lines, and is roughly within a factor of 2 of the oxygen-rich NGC 4449 SNR's [O III] luminosity. This is astounding, especially considering the density inferred from the [S II] lines is 5–10 times lower for this SNR than for N49 (Vancura et al. 1992), thereby suggesting a much larger filling factor of material contributing to the optical emission in the NGC 6946 SNR. The SNR's optical line flux over the spectral range 4800–7400 Å is 1.4×10^{39} ergs s^{-1}, and we estimate its total optical luminosity (L_{opt}; 3000–10,000 Å) to be around 2×10^{39} ergs s^{-1}. This luminosity is comparable to that of the

TABLE 2

COMPARISON OF BRIGHT SUPERNOVA REMNANTS

Parameter	N6946 SNR	N49 (LMC)[a]	N4449 SNR[b]
Distance	5.1 Mpc	50 Kpc	5.0 Mpc
Diameter	25 pc	20 pc	$\lesssim$1.5 pc
V_{opt} (km s^{-1})	≤400	≥200	3500
L(Hα) (ergs s^{-1})	1.9×10^{38}	2.9×10^{37}	...
L(S II) (ergs s^{-1})	1.6×10^{38}	2.6×10^{37}	...
L(O III) (ergs s^{-1})	4.2×10^{38}	1.4×10^{37}	8.8×10^{38}
L(opt) (ergs s^{-1})	2.0×10^{39}	1.2×10^{38}	1.7×10^{39}
L(X-ray) (ergs s^{-1})	2.8×10^{39}[c]	1.9×10^{37}[d]	8.0×10^{38}[e]

[a] Data from Vancura et al. 1992.
[b] Data from Blair et al. 1983.
[c] Schlegel 1994; 0.5–2.0 keV.
[d] Long et al. 1981; 0.15–4.5 keV.
[e] 0.2–4.0 keV.

NGC 4449 SNR and may represent an optical luminosity limit for SNRs. Just as in the case of the NGC 4449 SNR which is luminous due to its interaction with an H II region (Blair et al. 1983), we suggest this remnant's high luminosity is due to its expansion into dense surroundings. If, however, the surroundings are too dense, the SNR's observed optical (and X-ray) flux is reprocessed by grains into the IR (Shull 1980). Thus, this SNR in NGC 6946 may exhibit such a high luminosity due to both its interaction with dense interstellar gas but also due to a fortuitously low column density along our particular line of sight.

Table 2 also lists soft X-ray fluxes for the three SNRs. This NGC 6946 SNR is at least 3.5 times brighter than the NGC 4449 SNR in the soft X-ray band, with N49 a distant third. The high soft X-ray luminosity of the NGC 4449 SNR is attributed partially to dense circumstellar surroundings and partly to enhanced abundances (i.e., ejecta from the SNR). If the emission from the NGC 6946 SNR arises from "normal" abundance material, its luminosity must be attributed to dense preshock gas. This can be estimated from equation (5) of Long et al. (1981) to be $n_X = 7.6$ cm^{-3}, assuming an emissivity of 4×10^{-23} ergs cm^{-2} s^{-1} (Hamilton, Sarazin, & Chevalier 1983), a filling factor of 0.25 (cf. Long et al. 1981), and the diameter from above. This is slightly higher than the preshock density estimated from the optical lines above (assuming no magnetic fields), which is surprising since one would expect the optical estimate to apply to density enhancements which have cooled more rapidly than the X-ray gas (i.e., there should be rough pressure equilibrium between the X-ray and optical gas (i.e., there should be rough pressure equilibrium between the X-ray and optical gas). This may provide some evidence that magnetic fields or cosmic ray pressure are not negligible in this object.

VLA measurements of the region including the SNR are available (Van Dyk et al. 1994). These measurements show the SNR to have a 20 cm flux of ~1.6 mJy, which is fainter than the NGC 4449 SNR by at least a factor of 10 (cf. Bignell & Seaquist 1983). Also, the spectral index between 20 and 6 cm may be considerably steeper. By comparison, using the data from Mathewson et al. (1983) for N49, we calculate this object would only have a 20 cm flux of 0.15 mJy at the distance assumed for NGC 6946. Since N49 is definitely interacting with a complex multiphase ISM, the larger flux for the NGC 6946 SNR may also be indicative of dense circumstellar material. Hence, the most consistent picture of this object is that it is an older version of the NGC 4449 SNR, where interactions with dense surroundings have slowed the ejecta and diluted it with swept-up ISM.

Assuming this SNR has been emitting at this rate for the last century, an estimated total optical, UV, IR, and X-ray luminosity of around 10^{40} ergs s^{-1} would imply an energy loss of $\sim 3 \times 10^{49}$ ergs over this time period. Unless this object had a very high explosion energy or is the remnant of multiple SN explosions, it cannot keep up this prodigious energy output for very long. Assuming current flux levels and an explosion energy of 10^{51} ergs, we estimate the SNR's age at ≤ 3500 yr. Multi-wavelength monitoring of this object looking for flux levels changes might prove fruitful. In any event, it is clear that this object represents an extreme type of SNR, and one that is likely to provide new insight into the SNR phenomenon.

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