A Second UV “Light Bulb” behind the SN 1006 Remnant

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ABSTRACT

A point X-ray source located 9 arcmin northeast of the center of SN 1006 has been spectroscopically identified as a background QSO, with a redshift of 0.335. The object is moderately bright, with magnitude $V = 18.3$. If its ultraviolet spectrum is typical of low-$z$ quasars, this object will be a second (after the Schweizer-Middleditch star) source to use for absorption spectroscopy of material within SN 1006. Absorption spectra provide a unique probe for unshocked ejecta within this supernova remnant, and can possibly solve the long-standing problem of “missing” iron in the remnants of Type Ia supernovae.

Subject headings: ISM: individual: (SN 1006) — quasars: general — supernova remnants — supernovae: individual (SN 1006) — ultraviolet: ISM

1. Introduction

As the remnant of the brightest supernova to have been witnessed in recorded history, SN 1006 has long held interest for astronomers working at a variety of wavelengths using varied techniques. Among the most powerful of these has been the measurement of absorption lines in the ultraviolet spectrum of a hot subdwarf star (commonly referred to as the “SM star”), discovered and classified as sdOB by Schweizer and Middleditch (1980). The fortuitous location of this star behind SN 1006, only 2.5 from the projected geometric center of the remnant, provides an unusual opportunity to study the distribution of cold SN ejecta through absorption spectroscopy. Very broad UV resonance absorption features due to Fe II were first detected in IUE spectra of the SM

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star by Wu et al. (1983; see also Fesen et al. 1988). Subsequent spectra from the FOS on HST led to positive identification of additional broad absorption lines of Si II and Si IV, in addition to greatly improved measurements of the Fe II lines (Wu et al. 1993; 1997).

Iron in SN 1006 is of special interest, since it is the suspected remnant of a Type Ia event (Minkowski 1966; Schaefer 1996), and conventional models for SN Ia require the eventual production of several tenths of a solar mass of iron—from the decay of the $^{56}$Ni which powers the SN Ia light curve (Colgate & McKee 1969; Arnett 1979; Nomoto, Thielemann, & Yokoi 1984; an extensive set of models and references to more recent literature is given by Höflich & Khokhlov 1996). However, the Fe II absorption line measurements indicate only 0.014 $M_\odot$ of Fe$^+$, short of the expected total Fe mass by a factor of 20 or more. A new analysis of the FOS data using a different method of continuum fitting by Hamilton et al. (1997) leads to 0.029 $M_\odot$ of Fe$^+$, but is still far short of predictions for the total mass of Fe. In other young remnants of probable Type Ia SN, Tycho and Kepler, strong X-ray lines from highly-ionized iron result in large part from ejecta that have been excited by a reverse shock, but the absence of such lines in SN 1006 indicates that iron in the ejecta cannot yet have been shocked, so must still be relatively cool. Hamilton & Fesen (1988) considered various states in which iron could be hidden: the absence of Fe I absorption features excludes the possibility of significant gaseous neutral iron, while the absence of strong IR emission provides evidence against the formation of grains (iron-rich or otherwise) in the ejecta. They suggested that a significant amount of Fe might be more highly ionized, but far-UV spectra of the SM star obtained by Blair, Long, & Raymond (1996) from HUT show only weak Fe III absorption and severely limit the amount of Fe$^{++}$. Where several tenths of a solar mass of iron might be hiding in SN 1006 remains a mystery.

Further UV absorption spectroscopy of SN 1006, especially probing different lines of sight through the remnant shell, would certainly be important, but one is, of course, limited by the availability of background UV “light bulbs” which are appropriately placed and bright enough for observation. We report here the discovery of a second, moderately bright UV source within SN 1006: a QSO located 9′ NE from the projected center of the remnant shell.

2. Observations and Results

In an observation of SN 1006 from the ROSAT HRI, we noted an unresolved X-ray source, located in the NE region of the remnant shell, with no obvious optical counterpart (Winkler & Long 1997; hereafter Paper I). (In addition, a second, brighter, X-ray source near the center of the remnant shell, as well as three fainter sources outside, all coincide with bright, $V \sim 9–10$, foreground stars.) The unidentified NE source is also apparent in the PSPC images of Willingale et al. (1996), especially the image at $E > 1.5$ keV, indicating that it is a relatively hard source. The HRI count rate was measured at 5 counts ksec$^{-1}$, equivalent to $\sim 2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–2.5 keV) for a hard-spectrum source. In the Hα image from Paper I, the only evident object within the 5′ error radius for the NE X-ray source was what appeared to be a star estimated at
about magnitude 17. Located at RA (2000) = 15h 03m 33s.93, Dec (2000) = −41° 52′ 23″.7, this object is only 3″.7 from the position of the HRI X-ray source, well within the HRI error circle.

On 1997 March 29, we obtained a spectrum of this candidate object from the CTIO 1.5m f/7.5 telescope and R-C spectrograph. The spectrograph was configured with a 300 line mm$^{-1}$ grating blazed at 4000 Å and a Loral 1200 × 800 pixel CCD, to give wavelength coverage of 3500–7000 Å at a dispersion of 2.9 Å pixel$^{-1}$. A spectrograph slit width of 3″.5 gave a resolution of 9 Å. The candidate was observed under photometric but brightly moonlit conditions for a total of 4000 s, split among 4 frames of 1000 s each. All the data reduction has been carried out using conventional IRAF$^2$ reduction techniques: flat-fielding using a combination of dome flats and internal quartz flats, secondary “illumination correction” using twilight sky flats, and wavelength calibration from an internal He-Ar source. Flux calibration was achieved by observing several spectrophotometric standards from Hamuy et al. (1992).

The extracted spectrum is shown in Figure 1. The relatively flat spectrum and pattern of broad and narrow emission lines is typical of QSOs. The strongest line is Mg II $\lambda 2798$, redshifted into the blue end of the optical spectrum with velocity width $\sim 7000$ km s$^{-1}$ (FWHM). Also evident are broad H$\beta$ and narrow [O III] $\lambda\lambda 4959, 5007$, at the red end of the spectrum. A redshift $z = 0.335 \pm 0.001$ is consistent with all the identified features.

We have also obtained broad-band images of the NE region of SN 1006 from the CTIO 0.9 m telescope, equipped with the Tektronix No. 5 2048 × 2048 pixel CCD, on 1997 February 10. This combination gives a field of 13″.7 at a scale of 0″.40 pixel$^{-1}$. Exposures of 1200, 240, and 240 s, respectively, were obtained in the $U$, $B$, and $V$ bands under photometric, moonless conditions. These were reduced using standard IRAF procedures for overscan subtraction and flat-fielding based on well-exposed twilight sky flats. Photometric calibration was based on exposures of several Landolt (1992) and Graham (1982) fields. Figure 2 shows a section of the $V$ band image with the error circle for the HRI X-ray source indicated. The QSO position given above was measured from this image, using 18 surrounding stars from the HST Guide Star Catalog to define the reference frame.

Photometry of the object which was subsequently identified as a background QSO indicates unusual, very blue, colors: $V = 18.32 \pm 0.05$, $B - V = 0.17 \pm 0.04$, $U - B = -0.78 \pm 0.04$. This is significantly fainter than our earlier estimate (paper I) of about magnitude 17, based on a narrow-band H$\alpha$ image. The difference is most likely due to the fact that the QSO redshift of 0.335 shifts the wavelength of H$\beta$ emission into the bandpass of our H$\alpha$ filter.

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$^2$IRAF is distributed by the National Optical Astronomy Observatories, operated by AURA, Inc., under contract from the National Science Foundation.
3. Discussion

The discovery of another quasar at low redshift would be entirely unnoteworthy were it not for its location. But through its felicitous placement behind the SN 1006 remnant, this object becomes potentially quite valuable as an ultraviolet continuum source against which to measure absorption lines. As we noted in Section 1, the one line of sight through SN 1006 which has so far been probed, \textit{i.e.}, that to the SM star, has yielded rich information while deepening the mystery of where the iron in this supposedly Type Ia remnant may be hiding. The broad absorption lines of Fe II and Fe III measured with the \textit{HST} FOS and \textit{HUT}, respectively, demonstrate convincingly that a significant amount of fast-moving, cold iron is present within the remnant shell, but the inventory of Fe\textsuperscript{+} and Fe\textsuperscript{++} obtained from spherically symmetric models based on this single line of sight falls short of the \(\sim 0.3\ M_\odot\) of iron predicted from models for Type Ia supernovae by a factor of at least 10, and perhaps 20 or more.

The absorption line measurements for the SM star lead to another problem as well: how to keep ejecta expanding at the velocity indicated by the widths of the absorption lines within the confines of the remnant shell, without placing SN 1006 too far away. As we discussed more fully in Paper I, the velocity width for the cold iron, together with the known age of the remnant, gives a minimum extent for ejecta along the line of sight which is barely smaller than the transverse dimensions of the outer remnant shell at a distance of 1.8 kpc—the value inferred from proper motions of the optical filaments measured by Long, Blair, & van den Bergh (1988), together with the velocity of the shock as measured spectroscopically in these same filaments by Laming \textit{et al.} (1996). Hamilton \textit{et al.} (1997) reanalyzed the absorption data for the SM star and concluded that the near-side, blueshifted velocity is smaller than that originally measured by Wu \textit{et al.} 1993. With this result and a geometry which is elongated along the line of sight, they were able to achieve a self-consistent model for SN 1006.

Both these problems—the “missing iron” and the geometry-distance puzzle—may be elucidated by probing the distribution of ejecta along a second line of sight through SN 1006. The QSO is well placed for this purpose, located 9' away from the remnant center, \(\sim 58\%\) of the shell radius in this direction, compared with 2'5 for the SM star (see Figure 3). Absorption would, of course, be observed only from material which lies outside the the projected radius to the line of sight, so an ejecta ion species concentrated entirely within \(\lesssim 58\%\) of the shell radius would produce no absorption. But for a species which is smoothly distributed around a spherical shell of radius \(\gtrsim 60\%\) of the shell radius, the line of sight to the QSO may have a larger optical depth and narrower velocity width than that to the SM star. Absorption spectra and comparison of line profiles to the two sources for all species which have been observed in the SM star—Fe II, Fe III, Si II, Si III, and Si IV—would be important for constraining the geometry of the ejecta distribution and the radius of the reverse shock in SN 1006.

Is the QSO bright enough to measure absorption profiles? We have redshifted the composite spectrum from 101 QSOs observed with the \textit{HST} FOS (Zheng \textit{et al.} 1997) to \(z = 0.335\) and scaled
it to match the QSO spectrum from Figure 1 in the region of overlap. The extinction is unknown, but we have assumed a value \( E(B - V) = 0.12 \), the same as that measured for the SM star (Blair et al. 1996). The continuum is nearly flat at \( F_\lambda \sim 3 \times 10^{-16} \text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \) over the range 2200–3500 Å, about a factor of 50 fainter than that of the SM star at the wavelengths of the strong Fe II lines, \( \lambda 2383 \) and \( \lambda 2600 \). Nevertheless, the QSO is sufficiently bright that high quality UV spectra can be obtained with modest exposures using the new imaging spectrograph on the Hubble Space Telescope.

There is an interesting application for the QSO behind SN 1006 for X-ray astronomy as well. The brightest part of the X-ray shell is in the NE, passing only 6′ away from the QSO. Since the QSO is a point source of X-rays, it is potentially an excellent fiducial point for measuring the position and proper motion of the X-ray shell in this area. This is the same region in which Koyama et al. (1995) argued for a synchrotron origin for the X-ray emission based on the absence of X-ray lines in the ASCA spectrum. In Paper I, we showed a detailed correlation between the X-ray morphology observed with the ROSAT HRI and that observed in radio from the VLA by Reynolds & Gilmore (1986). Moffett, Goss, & Reynolds (1993) have measured the radio expansion rate for the entire shell at \( 0.44 \pm 0.13 \text{arcsec yr}^{-1} \). This differs somewhat from the proper motions for the H\( \alpha \) filaments of \( 0.30 \pm 0.04 \text{arcsec yr}^{-1} \) determined by Long et al. (1988), but the optical value was specifically for the NW filaments, while the radio value was for the overall expansion of the shell. It would be interesting to determine the X-ray proper motion at a specific shell location. Measurement of the expected differences of a few arcsec over a baseline of several years would be marginal at best based on the typical aspect uncertainty of \( \sim 5′′ \) for the ROSAT HRI, but the presence of a fiducial reference so close to the X-ray shock front would make measurement of the proper motions feasible.

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Fig. 1.— Optical spectrum of the counterpart to the X-ray source shown in Figure 2, now identified as a QSO at redshift 0.335.

Fig. 2.— A section of the $V$ band image of the NE region of SN 1006, showing the 10$''$ diameter error circle for the X-ray point source noted by Winkler & Long (1997). The object within the circle is the QSO with the spectrum shown in Figure 1. Several background galaxies may also be seen, indicative of the low extinction in the direction of SN 1006. The illustrated section measures exactly 6$'$ × 6$'$; north is up and east is to the left.

Fig. 3.— Smoothed X-ray map (from Winkler & Long 1997), showing the locations of the newly discovered QSO and the SM star within the SN 1006 shell. The plus indicates the center of the remnant. The frame measures 40$'$ × 40$'$. 
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