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# HIGH-VELOCITY IRON ABSORPTION LINES IN SUPERNOVA REMNANT 1006

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## ABSTRACT

The *International Ultraviolet Explorer* spectrum of the Schweizer-Middleditch star projected near the center of supernova remnant SNR 1006 shows an sdOB star continuum, with very strong, broad absorption lines. Strong $Fe^+$ resonance absorption lines are present. Their centers show zero radial velocity, while their profiles are broadened by $\sim$ 5–6 $\times 10^3$ km s$^{-1}$. Redshifted $Si^{+, +2, +3}$ lines at $v_r \sim 5 \times 10^3$ km s$^{-1}$ have also been tentatively identified. We argue that the absorptions must occur in the ejecta of the supernova. The strength and symmetric width of the $Fe^+$ lines suggests that the bulk of the ejecta is iron, in agreement with the current theory for the origin of Type I supernovae. The previous failure to detect strong Fe emission lines in the X-ray spectrum of this and other young Type I SNRs suggests that the ejecta may not have had time to interact significantly with the ambient medium. The presence of redshifted absorption lines due to supernova ejecta in its spectrum indicates that this star is located behind the SNR and is not physically associated with it.

*Subject headings:* line profiles — nebulae: supernova remnants — ultraviolet: spectra

## I. INTRODUCTION

During a search for a stellar remnant of SN 1006, Schweizer and Middleditch (1980) found a faint blue star ($V = 16.74$, $B - V = -0.14$) near the projected position of the center of the supernova remnant. Optical observations indicate that this object, which we refer to as the SM star, is a subdwarf sdOB star, with a spectroscopically derived distance of $d \approx 1.1$ kpc. Since such early subdwarfs are rare (see also Simon, Hunger, and Kudritzki 1981), and the stellar distance agrees roughly with the estimated distance to the supernova remnant (SNR), Schweizer and Middleditch suggested that this star might indeed be a remnant of the Type I SN 1006.

The identified stellar remnants of supernovae are all neutron stars, while the SM star is less compact than a white dwarf. There are at least two suggestions that white dwarf or subdwarf stars might be produced as remnants of Type I supernovae. First, Leventhal and McCall (1975) suggested that in a Type I supernova a white dwarf star containing $\sim 0.2\ M_\odot$ of $^{56}$Ni is inside of the expanding envelope of ejecta. However, Savedoff and Van Horn (1982) have argued that such a star could not have cooled to the temperature of the SM star in the time since the supernova. Second, it may be that some or all Type I supernovae occur when a white dwarf in a binary system accretes to a total mass greater than the Chandrasehkar limit (Whelen and Iben 1973). It is possible that the binary companion might be a giant star filling its Roche lobe; this situation would at least guarantee a large accretion rate. Then, the supernova explosion would blow away the envelope of the giant companion (Wheeler, Lecar, and McKee 1975), leaving behind its partially degenerate core, which might well resemble the sdOB SM star.

There is growing support for the theory that Type I supernovae result from the carbon detonation or deflagration of a white dwarf or the degenerate core of a moderate mass ($\sim 9\ M_\odot$) star (see Wheeler 1982, and references therein). The explosion, which completely disrupts the progenitor star, releases $\sim 1\ M_\odot$ of $^{56}$Ni, which then decays by electron capture to form $^{56}$Fe. These models have been successful in explaining the light curves, luminosities, and late-time spectra of Type I supernovae.

However, such a large amount of hot Fe has *not* been detected in the X-ray spectra of SNR 1006 nor in the other historical Type I SNRs Tycho and Kepler (Becker *et al.* 1980*a*, *b*, *c*). Thus, either the current model for Type I supernovae is wrong, or the ejecta in these remnants have not yet been heated to X-ray emitting temperatures through their interaction with a significant amount of ambient gas. In the latter case, we would expect to find ~ 1 $M_{\odot}$ of relatively cold iron moving at ~ $10^4$ km $s^{-1}$ in the centers of these SNRs (Hamilton and Sarazin 1983). This cold Fe could be detected most readily through its UV absorption lines, particularly the strong Fe II lines.

## II. OBSERVATIONS

Observations of the SM star were made with the short-wavelength prime (SWP) and the long-wavelength redundant (LWR) cameras on board the *International Ultraviolet Explorer* (*IUE*) satellite (Boggess *et al.* 1978). The spectrum of the SM star consists of exposure numbers SWP 16054 (360 minutes on 1982 January 16.9 UT) and LWR 12360 (440 minutes on January 18.9 UT). The two observations were processed by the *IUE* observatory staff with the routine production schemes.

The combined short-wavelength and long-wavelength spectrum of the SM star is shown in Figure 1 together with that of HZ 29, a hydrogen-deficient white dwarf star with a similar ultraviolet continuum. On these plots, the strong geocoronal Lyman-$\alpha$ emission from 1203 Å to 1226 Å and the reseau marks on the face plate of the cameras have been removed. The emission spike at 1663 Å is commonly seen in long exposures and is caused by a blemish on the camera face. At $V = 16.7$, the SM star is near the sensitivity limit for *IUE*. As a result, the SWP image is underexposed, and its signal-to-noise ratio degrades toward shorter wavelengths. The LWR camera has low sensitivity between 2000 Å and 2300 Å; this region of the spectrum is very noisy, and we have

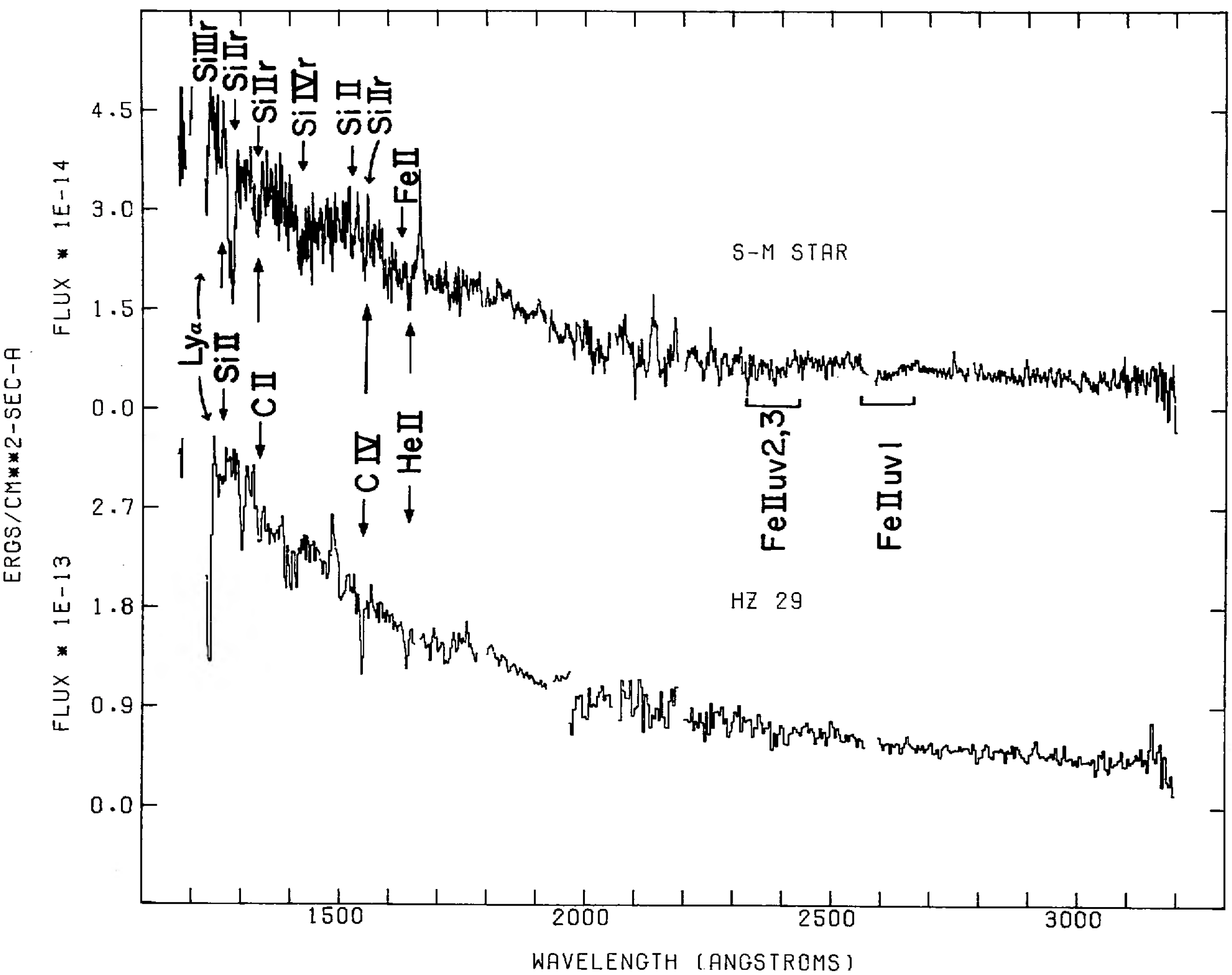


FIG. 1.—The UV spectra of the SM star and the white dwarf HZ 29. Line features from Table 1 are marked.

not attempted to identify any apparent spectral features there.

### III. RESULTS

The UV spectrum of the SM star shows a number of strong absorption features, which are listed in Table 1. In each case we give the centroid wavelength, $\lambda$, an estimate of the equivalent width, $W$, a very crude estimate of the FWHM of the line, and a suggested identification which is discussed below.

#### *a*) *Normal Stellar Features*

A number of the lines in Table 1 are normal stellar lines expected in a star of this spectral class; these include He II $\lambda$1640, C IV $\lambda$1550, Si II $\lambda$1260 and $\lambda$1527, and possibly C II $\lambda$1335 and Lyman-$\alpha$. These lines do not show any detectable velocity shift and are relatively narrow.

The white dwarf HZ 29 has a UV continuum with a similar shape to that of the SM star. Both stars have similar effective temperatures, surface gravities, and helium abundances. Thus, one might expect that they would show similar stellar absorption features, unless they have very different heavy element abundances. The C II, C IV, He II, and possibly Ly$\alpha$ lines appear to be present in both stars, while the Si II stellar features are strong only in the SM star. However, Figure 1 shows that the SM star has a number of strong absorption lines which do not appear in the spectrum of HZ 29.

#### *b*) Fe II *Lines*

Very strong, broad absorption features are observed which are due to the Fe II UV 1, 2, and 3 multiplets; weaker features may also be present at the wavelengths of the weaker UV 8 and 9 multiplets. It is unlikely that these strong Fe II lines arise in the atmosphere of the SM star, for three reasons. First, at the effective temperature of the SM star, little iron would be in this low ionization state (note that Fe II lines are not seen in the HZ 29 spectrum). Second, only allowed absorptions out of the ground multiplet are observed. In a high-density stellar atmosphere, absorptions out of excited states would also be present, such as the strong lines in the optical multiplets 27, 37, 38, and 42. The absence of nonresonant lines suggests that the absorptions occur in a lower density "interstellar" region along the line of sight to the SM star.

Third, the Fe II lines are extremely broad, much broader than any of the observed stellar features. Figure 2 shows the observed spectrum in the region of the Fe UV 1 multiplet. We have considered three possible causes for this broadening. First, the instrumental broadening for this observing mode is FWHM = 9.2 Å. Second, the line may be Doppler broadened by the motion of ejecta within the SNR. Third, the UV 1 multiplet contains a large number of possibly blended lines in this wavelength range. The relative strengths of these individual lines depends on whether the excited fine-structure levels are populated, and whether the individual line components are saturated. Without velocity broadening, it was not possible to reproduce the observed line widths from the instrumental resolution with any fine-structure populations or degree of saturation. In Figure 2, the line shapes for the two extreme cases (no fine-structure, unsaturated lines; fine-structure, saturated lines) are shown.

We believe the width of the Fe II lines must be due to Doppler broadening. From the full width of the Fe II UV 1 line, the absorptions are apparently occurring in a gas moving with velocities in the range $v_r \approx \pm 5\text{–}6 \times 10^3$

TABLE 1

ULTRAVIOLET ABSORPTION LINES

| $\lambda$ (Å) | $W$ (Å) | FWHM (Å) | Identification |
|---|---|---|---|
| 1228 .... | 3.0 | 10 | Si III $\lambda$1206.5 at $v_r \approx$ 5290 km s$^{-1}$ and/or the broad wings of stellar Ly$\alpha$ |
| 1258 .... | 1.6 | 8 | Si II $\lambda$1260 and/or Fe II $\lambda$1260 |
| 1282 .... | 8.6 | 19 | Si II $\lambda$1260 at $v_r \approx$ 5190 km s$^{-1}$? |
| 1332 .... | 3.3 | 12 | C II $\lambda$1335 and/or Si II $\lambda$1304 at $v_r \approx$ 5200 km s$^{-1}$? |
| 1425 .... | 4.1 | 32 | Si IV $\lambda\lambda$1394,1403 at $v_r \approx$ 5700 km s$^{-1}$? |
| 1527 .... | 1.6 | 8 | Si II $\lambda$1527 |
| 1548 .... | 2.9 | 12 | C IV $\lambda$1549 and/or Si II $\lambda$1527 at $v_r \approx$ 4300 km s$^{-1}$? |
| 1598 .... | 3.7 | 18 | ? |
| 1620 .... | 3.5 | 16 | Fe II UV 8 $\lambda\lambda$1608–1639? |
| 1640 .... | 2.2 | 8 | He II $\lambda$1640 stellar |
| 2385 .... | 16.7 | ~ 70 | Fe II UV 2 and 3 |
| 2590 .... | 20.4 | ~ 70 | Fe II UV 1 |

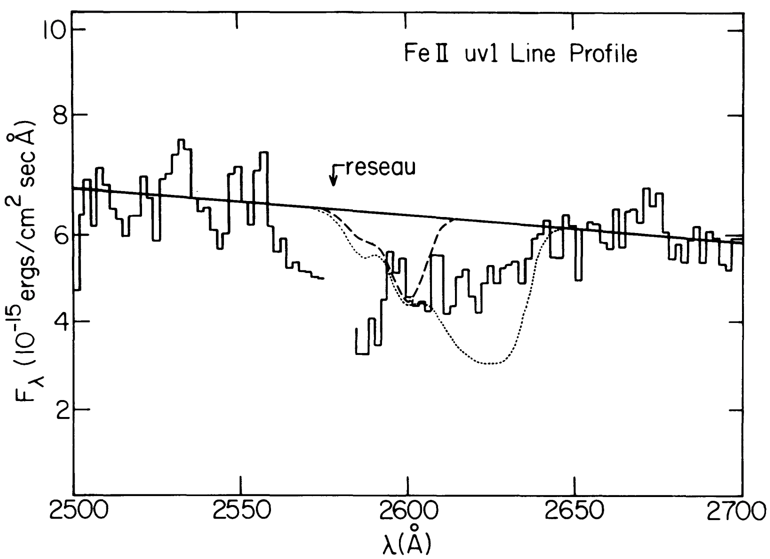


FIG. 2.—The Fe II UV 1 multiplet in the SM star. The solid curve shows the assumed continuum level. The dashed curve gives the line profile for instrumental broadening, no fine-structure excitation, and unsaturated lines. The dotted curve is for instrumental broadening, statistical weight fine-structure populations, and saturated lines.

km s$^{-1}$. The velocity range is nearly symmetric about zero velocity if the fine-structure levels are unpopulated.

### c) *Redshifted Silicon Lines?*

Several of the strongest absorption features in the spectrum, notably those at 1282 Å and 1425 Å, do not correspond to resonance absorption lines in any common ions which do not have stronger, unseen lines. Features at these wavelengths are not observed in the spectrum of HZ 29. The majority of these strong unidentified lines can be produced by redshifting all the strongest resonance lines of Si by 5–6 × 10$^3$ km s$^{-1}$. For example, the 1282 Å and 1425 Å features can be identified as redshifted Si II λ1260 and Si IV λ1400 respectively. While we believe that these identifications are tentative, they are at least consistent. That is, every strong line which should be present in the spectrum does correspond to an observed absorption feature, and to within the accuracy of the determination all the Si lines have the same redshift. However, the 1282 Å and 1425 Å lines are extremely broad, so that a considerable range of velocities must be present in the silicon absorbing region if these identifications are correct.

## IV. CONCLUSIONS

Strong absorption lines due to high-velocity ($v_r \approx \pm 5$–$6 \times 10^3$ km s$^{-1}$) iron have been detected in the UV spectrum of the SM star in the region of SNR 1006. Highly redshifted ($v_r \approx 5$–$6 \times 10^3$ km s$^{-1}$) absorptions due to silicon ions may also have been observed. We believe these absorptions occur in the freely expanding ejecta of the supernova. From the requirement that these ejecta have remained within the observed SNR, we derive a lower limit to the distance to SNR 1006 of 1.1 kpc for a spherical remnant. Since this lower limit is comparable to the observational upper limits on the distance to the remnant (i.e., Stephenson *et al.* 1977), the freely expanding ejecta must fill a substantial portion of the interior of the remnant.

One can derive a very crude estimate of the mass of iron in the ejecta from the equivalent width of the Fe II UV 1 line. We assume that the ejecta occupy a spherical volume of uniform density whose radius is just the expansion velocity times the age of the remnant. Then, a lower limit on the mass of iron is

$$M_{\rm Fe} \gtrsim 0.03\, M_\odot \left(\frac{\rm Fe^+}{\rm Fe}\right)^{-1}, \quad (1)$$

where Fe$^+$/Fe is the fraction of singly ionized iron. Equation (1) is an inequality because the numerical value was derived assuming the lines are unsaturated. If the identification of the 1620 Å feature with the UV 8 multiplet is correct, the lines must be significantly saturated.

While establishing an absolute abundance for iron is difficult, one can place limits on the abundance of Fe relative to other common elements which have strong lines from ions similar to Fe II. From the weakness of the lines from C II and Mg II, the Fe abundance relative to that of C and Mg apparently exceeds its cosmic value by at least an order of magnitude.

The strength and symmetrical width of the Fe lines in the SM star suggest that the bulk of ejecta from this Type I supernova may indeed be iron. Given the uncertain corrections to equation (1), an iron mass as high as $\sim 1\ M_{\odot}$ is certainly not inconsistent with the observations. The fact that strong absorptions are seen from Fe II, while strong Fe X-ray lines are not observed, indicates that the bulk of the supernova ejecta are still in nearly free expansion. Thus, SNR 1006 is in a young dynamical phase, in which there has been little interaction between the bulk of the supernova ejecta and any ambient interstellar or circumstellar matter. A similar situation may apply to the other young Type I SNRs, such as Tycho and Kepler, which also do not show strong X-ray line emission from iron. The enhanced abundances of Si and S in the X-ray emitting gas in these remnants may indicate that the outermost portions of the ejecta contain less chemically processed material. This is consistent with the possible detection of highly redshifted Si absorptions in the spectrum of the SM star.

From the fact that the Fe lines in the spectrum of the SM star are roughly symmetrical, including highly redshifted absorptions, we conclude that this star is located behind the SNR and is not physically associated with it.

The following crude model for SNR 1006 is consistent with these observations. The bulk of the ejecta is a symmetrical region of freely expanding iron. The outer portions of the ejecta are less chemically processed and include a large amount of Si. The ejecta are clumpy. One clump of Si on the far side of the SNR lies along the line of sight to the SM star and provides the highly redshifted Si absorptions. The blast wave proceeds into the ambient medium just ahead of the ejecta.

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