THE ASTROPHYSICAL JOURNAL, 320:597–601, 1987 September 15

THE INTERSTELLAR MEDIUM TOWARD SN 1987A

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Received 1987 April 14; accepted 1987 May 15

ABSTRACT

High-resolution spectra of SN 1987A obtained with the *International Ultraviolet Explorer* satellite show absorption features from the disk and halo of our Galaxy and the Large Magellanic Cloud. A rich variety of elements and ionization stages is found, including allowed resonance lines of abundant elements with ionization states ranging from C I and O I to Al III, Si IV, and C IV. The Si IV and C IV absorption at LMC velocities is unusually strong toward the supernova as compared to most other stars in the LMC and SMC. The origin of these lines is discussed.

Subject headings: galaxies: Magellanic Clouds — interstellar: matter — stars: supernovae — ultraviolet: spectra

I. INTRODUCTION

The discovery of a bright supernova in the Large Magellanic Cloud presents a remarkable ultraviolet source for studying the interstellar medium. When first observed with *IUE* (see Kirshner *et al.* 1987), the supernova was brighter by ~ 5 mag than other hot stars in the LMC and emitted enough ultraviolet flux to make high-dispersion ultraviolet observations with *IUE* quite easy. The exposures were short, minimizing particle background, and the background continuum was not distorted by the many P Cygni stellar profiles that are typical of hot stars, which frequently compromise the measurement of interstellar features.

We report here on the narrow absorption features detected in four high-dispersion spectra covering λλ1200–3200 that can be identified with the disk and halo of our Galaxy and with the Large Magellanic Cloud. A wide variety of ionization states are found, and a number of unidentified features are present. The low-dispersion spectra of the supernova are discussed in Kirshner *et al.* (1987).

II. THE SPECTRA

Four high-dispersion spectra were obtained through the large aperture of *IUE*, as detailed in Table 1. Spectra are reduced to heliocentric velocity by the *IUE* project, but there can be an additional uncertainty depending on the position of the target within the large aperture. We have corrected for this uncertainty by requiring that the galactic interstellar lines of C I (λ1656.928) and S II (λλ1250.586, 1253.812, 1259.520) have a heliocentric velocity of +18 km s^{-1}, corresponding to that of the interstellar Ca II lines toward a nearby star, R145 as measured by Blades (1980). This velocity is also in harmony with the reported (Andreani and Vidal-Madjar 1987) strong Ca II, Na I, and K I components from 7 to 22 km s^{-1} (heliocentric) toward the supernova itself. The correction to the SWP spectra amounts to −7 km s^{-1}. The LWP spectra were corrected by forcing the Fe II lines in the LWP spectra to agree in velocity with the Fe II transition in the SWP spectra (λ1608.456). This correction amounted to −25 km s^{-1}. Here we are using $V_{\rm helio}$ which for the LMC is related to $V_{\rm LSR}$ by $V_{\rm LSR} = V_{\rm helio} - 16$ km s^{-1}.

Selected portions of the spectra exhibiting ions of various stages are shown in Figures 1 and 2. Two prominent absorption features are generally present, a low-velocity component (~ 0 to +30 km s^{-1}) associated with the disk and low halo of our Galaxy, and a high-velocity component (about +240 to +280 km s^{-1}) associated with the Large Magellanic Cloud. The components at intermediate velocities may arise from the LMC, the Magellanic Stream, or both (Songaila *et al.* 1986), or the halo of our Galaxy (Savage and de Boer 1979, 1981). These features are similar in velocity to the ones detected in other high-resolution ultraviolet studies of LMC stars (Savage and de Boer 1979, 1981; de Boer and Savage 1980; Savage 1986) and are consistent with the many interstellar components found by Andreani and Vidal-Madjar (1987). A list of the strong lines that we have identified in SWP 30377 and LWP 10190 is given in Table 2. In addition to lines in the table, there are numerous other weaker features that will merit subsequent study. Some of these are listed at the bottom of Table 2.

Gas associated with the supernova itself might have high velocities or exhibit changes on short time scales. Inspection

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TABLE 1

FOUR HIGH-DISPERSION *IUE* SPECTRA OF SN 1987A

Image Number	Date (1987)	Time at Start (UT)	Exposure Time
SWP 30377	Feb 24	$21^h37^m11^s$	14 min
SWP 30379	Feb 25	$00^h53^m30^s$	14 min
LWP 10190	Feb 24	$22^h14^m00^s$	110 s
LWP 10192	Feb 25	$00^h45^m34^s$	100 s

of the spectra does not reveal any high-velocity components of strong lines up to several thousand kilometers per second. Careful comparison of these spectra, which were obtained a few hours apart, does not disclose any substantial variation in the appearance of the absorption features. SWP 30379 has lower signal-to-noise ratio than SWP 30377 since the ultraviolet continuum was rapidly weakening and the radiation background was significant, making weak features and line profiles more uncertain.

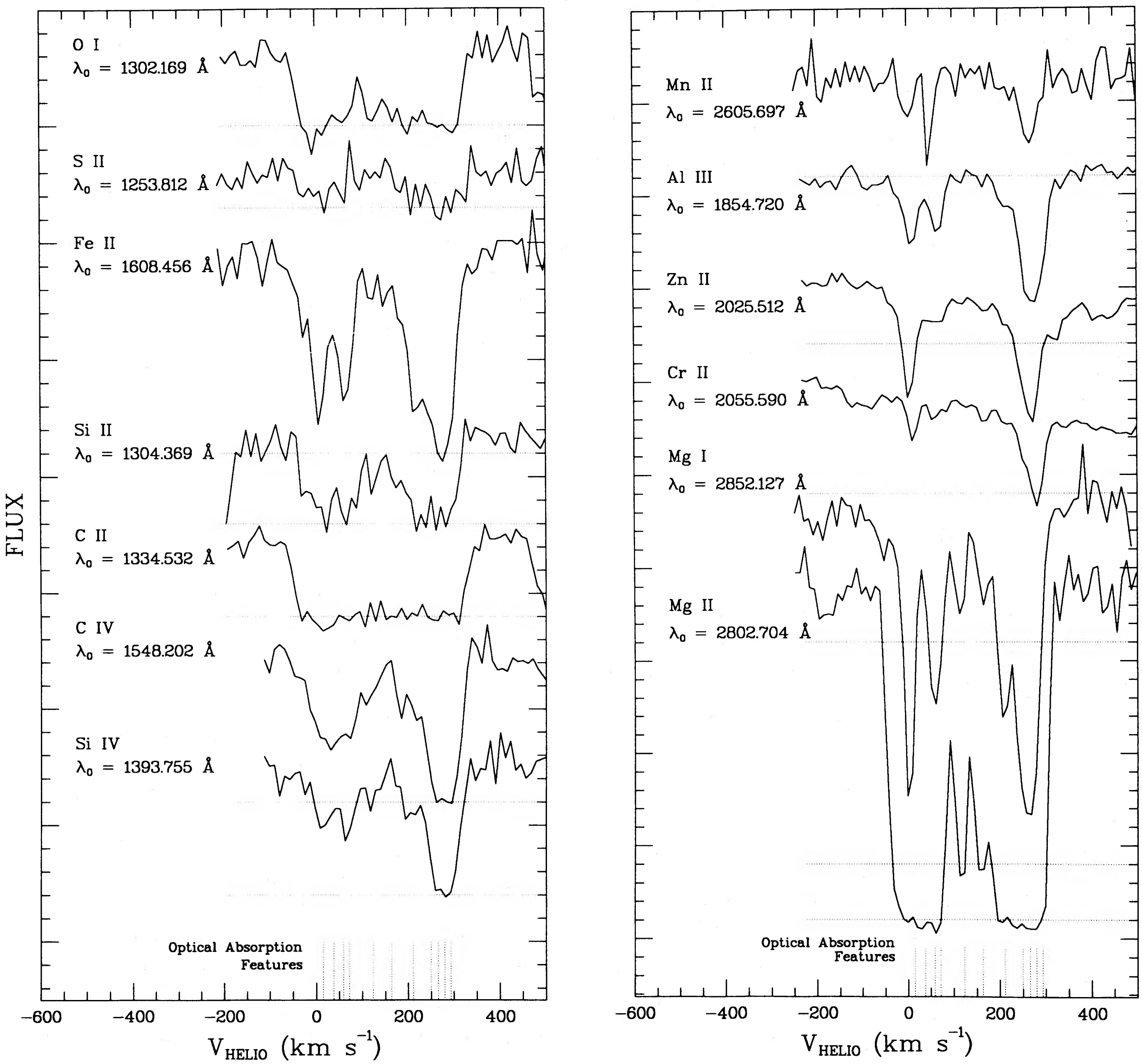

FIG. 1*a* FIG. 1*b*

FIG. 1.—(*a*) Selected absorption features from the short-wavelength spectrum (image SWP 30377). The zero level for each profile is indicated by a horizontal dotted line, and the Ca II absorption velocity components reported by Andreani and Vidal-Madjar (1987) are shown by vertical dotted lines at the bottom of the plot. The C II feature includes another component at $\lambda_0 = 1335.708$ Å. (*b*) Selected absorption features due to low-ionization stages extracted from SWP 30377 and LWP 10190.

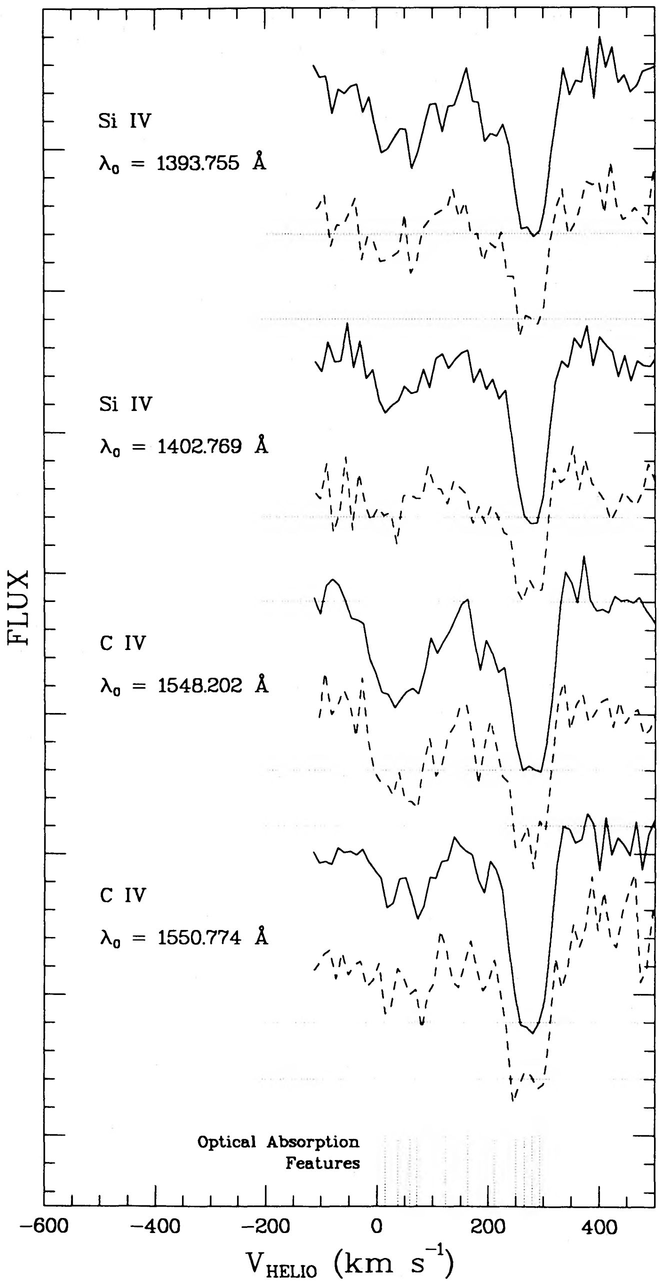

FIG. 2.—Si IV and C IV absorption profiles from SWP 30377 (*solid line*) and SWP 30379 (*dashed line*). Zero levels and Ca II velocities as in Fig. 1.

Equivalent widths were measured for many of the absorption lines (Table 3) by fitting a straight line to neighboring continuum regions by the method of least squares, and then integrating over the absorption line. Most of the lines reported are in well-exposed regions of the spectra, and uncertainties due to pixel-to-pixel noise and continuum level placement are $\sim$ 20 mÅ. The spectrum was extremely weak at 1240 Å, however, and we have no useful information about the N V lines.

III. DISCUSSION

The rich absorption line spectrum of SN 1987A appears similar to those obtained toward other LMC stars, with one significant difference. In the LMC component, the spectrum of SN 1987A shows the highly ionized species, Si IV and C IV, with significantly larger equivalent widths than found toward other nearby LMC stars. Inspection of the line strengths in Table 3, shows that the LMC components of low-excitation species are effectively the same in SN 1987A and two stars, HD 38282 and HD 36402, but the equivalent widths of the high-ionization species in SN 1987A exceed those of the stars by $\sim$ 200 mÅ. While excess column densities of $\sim 3 \times 10^{14}$ cm^{-2} could account for the enhanced equivalent widths in principle, the lines are so highly saturated that much greater column densities must be present. Close comparison of the Si IV λ1393 and C IV λ1548 profiles carefully obtained from stacked spectra by Savage (1986) toward HD 36402 with the same lines in SN 1987A shows that all profiles have the same extent in velocity at the continuum level. However, the core of the C IV line in the supernova reaches the zero level of intensity, whereas it does not in the star. In addition, the Si IV C IV lines in the supernova show a more distinct absorption feature near $V_{helio} = +200$ km s^{-1}.

Strong highly ionized interstellar lines have been observed before toward exceptional objects (Cassinelli, Mathis, and Savage 1981), such as the complex R136a in the LMC, which is now believed to contain as many as several hundred hot stars. SN 1987A is well removed from the core of 30 Dor, although there is some faint nebulosity nearby. In the SMC star HD 5980, which lies in an H II region, Si IV and C IV are

TABLE 2

INTERSTELLAR LINES: PRELIMINARY LIST OF IDENTIFICATIONS

A. SN 1987A–SWP 30377

Species	Wavelength (Multiplet)[a]
C I	1560.310(3), 1656.928(2)
C II.......	1334.532(2), 1335.708(2)
C IV	1548.202(1), 1550.774(1)
O I	1302.169(1)
Mg I......	?2025.824(2)
Al II	1670.786(2)
Al III	1854.720(1), 1862.795(1)
Si II	?1260.42(4), 1304.369(3), 1526.719(2), 1808.003(1)
Si III......	?1206.510(2)
Si IV......	1393.755(1), 1402.769(1)
S II	1250.586(1), 1253.812(1), 1259.520(1)
Cr II......	2055.590(1), 2065.460(1)
Fe II......	1608.456(8)
Ni II......	?1370.200(8), 1741.560(5), 1751.920(4)
Zn II......	?2025.512(1), 2062.016(1)

B. SN 1987A–LWP 10190

Species	Wavelength (Multiplet)[b]
Na I	?2852.811(1), ?2853.013(1)
Mg I......	2852.127(1)
Mg II	2795.528(1), 2802.704(1)
Mn II	2576.107(1), 2605.697(1)
Fe II......	2585.876(1), 2599.395(1), 2343.495(3), 2373.733(2), 2382.034(2)

[a] λ < 2000 Å, vacuum wavelength; λ ≥ 2000 Å, air wavelengths. Parentheses denote multiplet number. Unidentified features: λ1259.6, λ1717.1, λ1730.3, λ1832.7, λ2063.5, λ2067.5.

[b] λ ≥ 2000 Å air wavelength. Parentheses denote multiplet number.

TABLE 3

EQUIVALENT WIDTHS[a] OF SELECTED ABSORPTION LINES

Absorption Line	SN 1987A[b] (galactic)	SN 1987A[b] (150–300 km s^{-1})	HD 38282[c] (150–300 km s^{-1})	HD 36402[d] (150–300 km s^{-1})	HD 36402 (galactic)
C I λ1656.9	122	81	...	...	...
C IV λ1548.2	400	520	280	340	390
λ1550.8	180	460	250	160	250
O I λ1302.2	...	720	650	500	790
Mg I λ2852.1	592	750	...	...	...
Al II λ1670.8	...	760	700	680	870
Al III λ1854.72......	170	330	290	310	80
λ1862.79......	110	210	180	200	100:
Si II λ1304.4	522	534	550	480	610
Si IV λ1393.8	310	450	350	330	270
λ1402.8	130	380	300	300	130

[a] In milliangstroms.
[b] From SWP 30377 and LNP 10190.
[c] de Boer, Koorneef, and Savage 1980.
[d] de Boer and Savage 1980.

nearly comparable in strength (Fitzpatrick and Savage 1983) to that found toward SN 1987A.

We can speculate on several possible reasons for the increased strength of highly ionized species toward the supernova. The original high-energy flash in the supernova could produce a region of increased ionization around the object. However, theoretical models of the UV flash of a Type II supernova predict $\sim 10^{58}$ ionizing photons (Chevalier 1976), and the SN 1987A light curve suggests a smaller atmosphere than assumed in the standard Type II models which would lead to correspondingly smaller UV emission (see Kirshner *et al.* 1987). Thus the supernova UV flash is unlikely to produce a C IV, Si IV zone much bigger than 1 pc in size. Unless the ambient density in this region is $n \gtrsim 10$ cm^{-3}, the supernova ionization zone is unlikely to account for the strong Si IV and C IV. Since the recombination times of these ions are $\sim 10^3/n$ yr this hypothesis could predict measurable changes in the line profiles in a few years.

An alternative hypothesis is a preexisting stellar wind. Such a wind would have to be quite slow (less than 50 km s^{-1} as inferred from the width of the C IV line), suggesting a cool precursor star. This seems inconsistent with the likely identification of Sanduleak $-69°202$ as the precursor (Kirshner *et al.* 1987). There is, however, an absorption feature in C IV and Si IV near $V_{\rm helio} \approx +200$ km s^{-1} that might be associated with mass ejection from the precursor star.

A third hypothesis is that the supernova lies deeper or in a more highly ionized region in the LMC than previous targets for high-resolution spectroscopy. Although the low stages of ionization do not indicate more material toward SN 1987A (see Table 3), we cannot rule out the possibility that the line of sight contains an excess of highly ionized atoms perhaps resulting in part from photoionization and collisional ionization from the 30 Dor region.

The absorption at low and intermediate velocities is quite similar to that which Savage and de Boer (1979, 1981) identified with the Galactic halo. The spectra confirm the existence of discrete components at about +60 and +120 km s^{-1} in both low- and high-ionization species (see Savage and de Boer 1981; Songaila *et al.* 1986; Andreani and Vidal-Madjar 1987). The presence of such a wide range of ionization presents a challenge to theoretical models. Models of low-density photoionized gas (Fransson and Chevalier 1985) can account for the Si IV and C IV, but predict very little N V. Models of radiatively cooling gas (Edgar and Chevalier 1986) can account for C IV and N V (the latter ion is not detectable in our spectra, but it is likely to be present by analogy with the low Galactic corona observations of Savage and Massa 1987). The cooling models do not predict enough Si IV. Calculations performed with the shock wave code described in Cox and Raymond (1985) indicate that the inclusion of extragalactic EUV continuum radiation (as in Fransson and Chevalier 1985) and EUV emission from hot white dwarfs (Panagia and Terzian 1984) in the Edgar and Chevalier cooling model increases the Si IV column density to the observed value, provided that the gas cools at constant density, rather than constant pressure. Such constant density cooling might be expected in thermally unstable cooling in a galactic fountain (Shapiro and Field 1976). Higher density regions which had cooled at constant pressure could account for the low-ionization species.

In conclusion, the supernova provides an indication of unusually highly ionized gas along its line of sight in the LMC and confirmation of the observations of low- and intermediate-velocity gas discovered in *IUE* observations of other LMC objects. Space Telescope observations of stars near the supernova may reveal the nature of the highly ionized gas in that part of the LMC.

We thank Blair Savage, the referee, for helpful and timely comments. This research was supported in part by NASA grant NSG 5-87 to the Smithsonian Astrophysical Observatory, NAG 5-841 to the Harvard College Observatory, and NSF grant AST 85-16537 to the Harvard College Observatory.

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