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MILLION DEGREE GAS IN THE GALACTIC HALO AND THE LARGE MAGELLANIC CLOUD.
II. THE LINE OF SIGHT TO SUPERNOVA 1987A[1]

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ABSTRACT

We report the first detection of forbidden [Fe x] λ6375 absorption in the interstellar medium of the Large Magellanic Cloud in front of SN 1987A. The exceptional brightness of the SN provided a unique opportunity to obtain high-resolution spectra with signal-to-noise ratios in excess of 1000 and thereby extend previous searches for this line to significantly more sensitive detection limits. After consideration of contamination by telluric lines and diffuse interstellar bands, it is concluded that the [Fe x] absorption has an equivalent width $W_\lambda \geq 2.5$ mÅ and extends over the velocity range $v_\mathrm{H} \simeq 215$–270 km s^{-1}. The detection implies a high column density of coronal gas: $N(\mathrm{H})_\mathrm{HIM} \geq 3.2 \times 10^{21}$ cm^{-2}, comparable to that of neutral hydrogen detected in 21 cm emission: $N(\mathrm{H\ I}) = 2.75 \times 10^{21}$ cm^{-2}.

Possible sites of the [Fe x] absorption are considered. An origin in gas close to the SN and photoionized by the X-ray flash at shock breakout is difficult to reconcile with the likely weakness of this burst in SN 1987A and with the fact that no significant variations in the absorption were seen over time scales of months. A more likely interpretation is that we have detected 10^6 K gas associated with the supergiant H II region 30 Doradus—the largest concentration of massive stars in the Local Group of galaxies—where the combined effects of previous supernovae appear to have produced superbubbles in the interstellar medium with radii greater than 100 pc. Even so, the energy input required to maintain the high densities of coronal gas indicated by our observations is very high.

[Fe x] absorption due to gas in the disk and halo of the Galaxy cannot be recognized convincingly in our spectra; the upper limit $W_\lambda \leq 5$ mÅ is still well above estimates based on current models of a hot component of the interstellar medium. Further work using the brightest early-type stars in the LMC should help clarify some of these issues.

Subject headings: galaxies: Magellanic Clouds — interstellar: matter — nebulae: H II regions — stars: individual (SN 1987A) — stars: supernovae

I. INTRODUCTION

During the last few years there have been several attempts at detecting in *absorption* the forbidden lines [Fe x] λ6374.51 and [Fe XIV] λ5302.89 formed in interstellar gas at coronal temperatures. Although the lines are expected to be extremely weak, with equivalent widths $W_\lambda < 1$ mÅ (e.g., York and Cowie 1983), the incentive for such searches is high. If detectable with modern optical instrumentation, these transitions may provide the only way at present to sample 10^6 K gas over long path lengths in the Milky Way and nearby galaxies. The existence of a hot component of the interstellar medium is well established, primarily from observations of the diffuse soft X-ray background and of O VI absorption lines in the far-ultraviolet spectra of early-type stars (see Jenkins 1987 for a recent review). Yet, more than 15 yr since its discovery, we remain largely ignorant of the large-scale distribution and physical properties of the hot gas, since the ultraviolet data refer mostly to the solar neighborhood, while the location of the bulk of the X-ray emitting gas is controversial (e.g., Kahn and Jakobsen 1988 and references therein). As emphasised by Cowie and Songaila (1986), this is a serious impediment to the progress of our understanding of the interstellar medium, given the central role the hot component plays in current theories.

The search for interstellar [Fe x] absorption was pioneered by L. M. Hobbs, who, in a series of papers (Hobbs 1984*a*, *b*, 1985), reported upper limits as low as $W_\lambda \leq 3$ mÅ ($3\ \sigma$) over distances of 1–2 kpc from the Sun to a sample of 37 bright stars, mostly in the Galactic disk. Pettini and D'Odorico (1986; hereafter Paper I) subsequently extended this work to two distant stars in the Galactic halo and to the interstellar medium of the Large Magellanic Cloud, placing upper limits similar to those of Hobbs for [Fe x] absorption in either the Galaxy or the LMC.

These limits are, however, still well above the strength of the absorption expected on theoretical grounds (McKee and Ostriker 1977; Edgar and Chevalier 1986) and were essentially set by the photon statistics of the data, in turn determined by the brightness of the early-type stars observed. It is easy, then,

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[1] Based on observations obtained with the Anglo-Australian telescope at Siding Spring Observatory, Australia, and with the 3.6 m telescope of the European Southern Observatory, La Silla, Chile.

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to appreciate the unique opportunity offered by SN 1987A for this area of interstellar work. At maximum light SN 1987A reached $V = 2.95$ (Catchpole *et al.* 1987; Hamuy *et al.* 1988), nearly 8 mag brighter than R136a, the brightest stellar object in the LMC. This gave us the means to extend to significantly more sensitive limits our earlier search for [Fe x] λ6374.51 in the direction of the LMC, leading to the first detection of this line in absorption.

Section II below gives a brief account of the observations and the data reduction procedures. The results are presented in § III where the absorption features detected are critically examined to assess the likely contamination by nearby telluric lines and diffuse interstellar bands (DIBS). It is concluded that [Fe x] absorption is present at LMC velocities, whereas the reality of a Galactic counterpart remains open to the question. Although weak, the absorption implies a substantial column density of 10^6 K gas in the LMC. In § IV we discuss its possible origins, while in § V we suggest further observations which may be able to differentiate between the alternatives proposed. A preliminary report of this work has been given by D'Odorico *et al.* (1987). Observations of the [Fe x] spectral region in SN 1987A have also been reported, in parallel with the present work, by Malaney and Clampin (1988) whose results are in broad agreement with those presented here.

II. OBSERVATIONS AND DATA REDUCTION

The region of the SN spectrum near 6375 Å was observed on several nights between 1987 February and July from the European Southern Observatory at La Silla, Chile, and the Anglo-Australian Observatory, Siding Spring, Australia. Table 1 gives the journal of observations and relevant details of the data. The ESO observations used the 1.4 m coudé auxiliary telescope, with the coudé echelle spectrograph and Reticon detector. The AAT data were obtained with the 82 cm camera of the RGO spectrograph at the cassegrain focus of the telescope, using a 1200 lines mm^{-1} grating in second order and a GEC CCD as the detector.

Each SN exposure was bracketed by spectra of either a Th-Ar or a Cu-Ar hollow-cathode lamp, providing a wavelength scale and a measure of the instrumental resolution (by Gaussian fitting of the thorium and argon emission lines). For each night of observation, many exposures of a quartz lamp were obtained at the same grating setting as the SN spectra; these were then added together to produce a flat-field image subsequently used to correct the pixel-to-pixel variations in the photometric responses of the Reticon and CCD detectors. During the AAT observations the SN image was trailed continuously along the slit, so as to use approximately two thirds of the area of the CCD chip (~ 250 columns) to record the spectrum; in this way any residual fixed-pattern noise of the detector after flat-fielding is averaged out to a large extent. For the same reason, the grating angle was changed slightly between different exposures. Both Reticon and CCD are sensitive to cosmic-ray–induced events. In the ESO spectrum, affected pixels were corrected by interpolating between adjacent pixels. In the AAT data, columns containing invalid pixels (cosmic rays and cosmetic defects in the CCD chip) were identified and simply not included in the extraction of one-dimensional spectra from the CCD frames, thus avoiding the need to interpolate between adjacent columns with its attendant uncertainties.

The extracted spectra were rebinned to a linear wavelength scale, with a bin size chosen to sample the FWHM of the instrumental profile with ~ 2.2 bins. The final step in the reduction consisted of normalising the spectra by division by the underlying supernova continuum. This was determined by fitting a number of splines to portions of the SN spectrum free of narrow absorption lines (mostly telluric—see below) and outside the wavelength regions where Galactic and LMC [Fe x] absorption may be expected. A by-product of the spline fit to the continuum is a measure of the signal-to-noise ratio of the spectra, given by the rms variation of the data points from the fit.

As can be seen from columns (5), (7), (8), and (9) of Table 1, all our spectra are of high resolution (3–9 km s^{-1} FWHM) and very high signal-to-noise ratio (~ 400–1500). It was particularly gratifying to find that the special care taken in the observing and data reduction procedures resulted in values of the S/N of the final spectra which are only 10–15% lower than the limits set by the photon statistics. The last column of Table 1 gives the corresponding values of $W_\lambda^d(3\ \sigma)$, the 3 σ detection limits for the equivalent widths of narrow, unresolved absorption lines, as defined by Hobbs (1984*a*) and used in Paper I. Comparison with Table 2 of Paper I shows that the best limits reached in the SN observations ($W_\lambda^d = 0.4$ mÅ) represent an improvement by about one order of magnitude over those achieved previously toward R136a.

III. RESULTS

a) Absorption Lines near 6375 Å

Examples of the data are presented in Figures 1 and 2. In Figure 1*a* the SN spectrum obtained on April 9 is reproduced together with the continuum fit; the drop in counts toward longer wavelengths is due to the fact that, at this epoch, the interstellar features of interest were superposed on the blue side of the broad Hα P-Cygni profile in the SN. Figure 1*b* shows a portion of the same spectrum, normalized to the continuum and reduced to a heliocentric velocity scale appropriate to [Fe x] λ6374.51.

It is immediately obvious that the strongest feature in this region of the spectrum is at velocities between $v_{\rm H} \simeq 210$–365

TABLE 1

JOURNAL OF OBSERVATIONS OF [Fe x] λ6375 REGION IN SN 1987A

Date (1987) (1)	Telescope (2)	m_V (SN) (mag) (3)	Dispersion (Å mm^{-1}) (4)	Resolution (km s^{-1}) (5)	Exposure Time (s) (6)	Mean Counts/Bin (10^6) (7)	S/N (8)	$W_\lambda^d(3\ \sigma)$ (mÅ) (9)
Feb 28	ESO 1.5 m CAT	4.4	1.9	3.0	4500	0.2	400	0.4
Mar 9	AAT 3.9 m	4.3	2.7	9.2	2000	0.35	560	1.1
Apr 9	AAT 3.9 m	3.5	2.7	9.2	1000	1.8	1170	0.5
Jul 20	AAT 3.9 m	4.6	2.7	9.5	2400	3.1	1510	0.4

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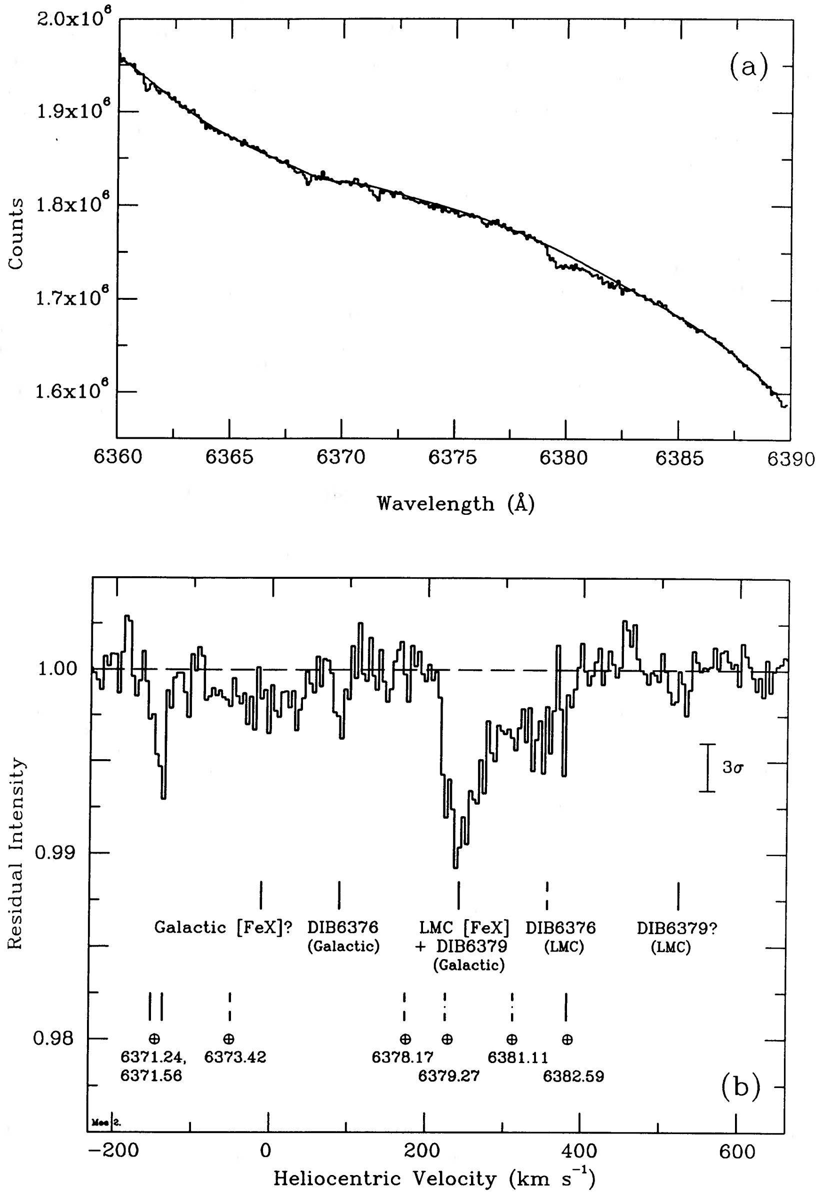

FIG. 1.—(*a*) AAT spectrum of SN 1987A in the region of [Fe x] λ6375 obtained on 1987 April 9. The adopted continuum level is also shown. (*b*) Portion of the April 9 SN spectrum normalized to the continuum and reduced to a heliocentric velocity scale appropriate to [Fe x] λ6375.51. Note the greatly expanded vertical scale, encompassing only 3% of the recorded signal. Vertical tick marks indicate the positions of interstellar (*upper row*) and telluric (*lower row*) absorption lines occurring in this spectral region. Three types of tick marks are used to denote, respectively, features detected (*continuous ticks*), features below the detection limit (*broken ticks*), and features which are likely to be above the detection limit but are blended with other lines (*dot-dash ticks*). The vertical bar labeled 3 σ shows 3 × the measured rms deviation of the data points from the continuum fit.

km s^{-1}; the corresponding equivalent width is $W_\lambda = 16.3 \pm 0.6$ mÅ. This is approximately the velocity interval over which interstellar absorption by LMC gas is expected. For example, the ultraviolet C IV, Si IV, and Al III lines recorded by Blades *et al.* (1988) with *IUE* show absorption extending from $v_{\rm H} \simeq 180$ to $\simeq 330$ km s^{-1}. This velocity coincidence strongly suggests that we have indeed detected [Fe x] λ6375 absorption due to coronal gas in the LMC. However, in order to be confident of this conclusion and to quantify the strength of the absorption, it is necessary to examine critically alternative identifications for the feature we have detected. This is particularly important given the unusually high S/N of our data and the weakness of the line under consideration.

In assessing the degree of contamination of the [Fe x] λ6375 region by unrelated lines we are greatly aided by the careful analysis of this problem by Hobbs (1984*a*, 1985). His work showed that a number of telluric lines and a pair of diffuse interstellar bands, DIB λλ6376.08, 6379.30, complicate the interpretation of this spectral region. Consequently, we have used the measured equivalent widths of telluric lines and DIBS which are unblended with possible [Fe x] absorption to estimate the *maximum likely contribution* to the absorption we have detected at [Fe x] velocities.[4] The analysis is summarized

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[4] In early-type stars a number of stellar absorption lines can be a source of additional confusion; these, however, do not concern us directly here, as any intrinsic SN features were far too broad—at the epochs of our observations—to be mistaken for interstellar absorption lines.

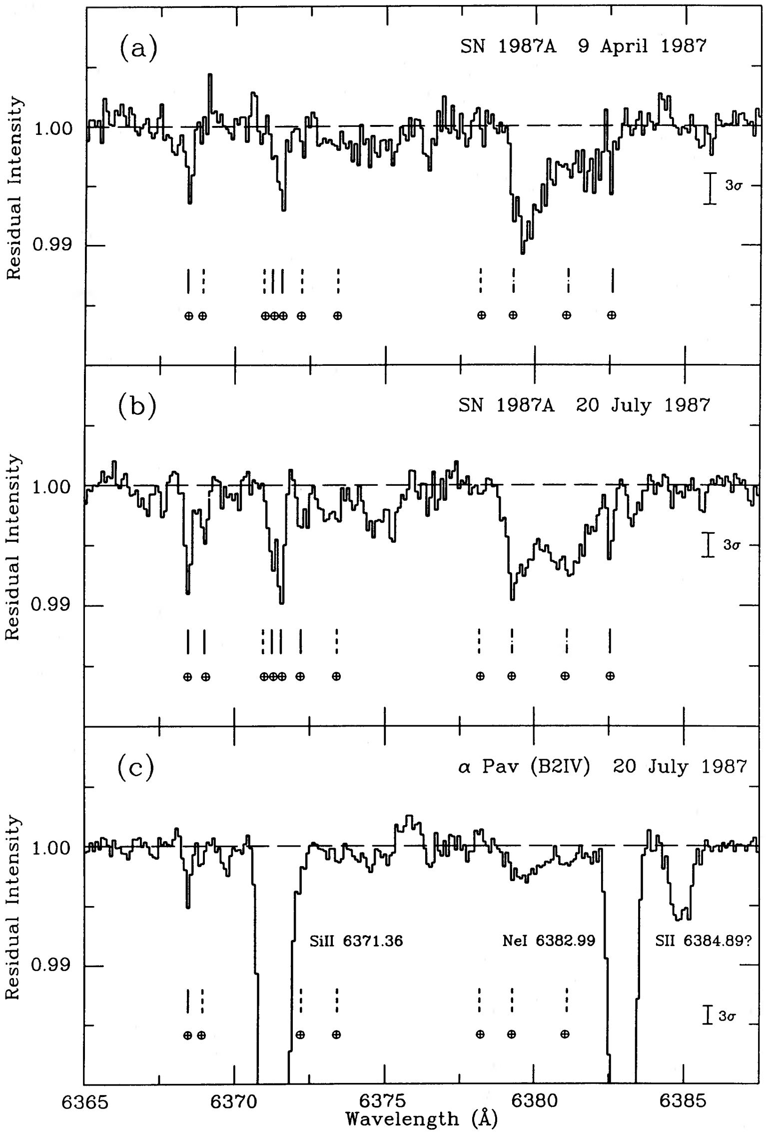

FIG. 2.—Comparison of the [Fe x] region in spectra of SN 1987A obtained at two epochs (*a* and *b*), and in the spectrum of α Pavonis, a nearby early-type star (*c*). All three spectra have been normalized to the underlying continua, determined as described in the text. The vertical tick marks show the measured and expected positions of telluric lines, using the same convention as in Fig. 1*b*. The strong absorption features in the spectrum of α Pav are stellar lines, as labeled.

in Table 2 and the features of interest are indicated in Figures 1*b* and 2. In Figure 2, in particular, we compare the SN spectrum at two epochs, April 9 and July 20; since telluric lines are $\approx 30\%$–50% stronger in the latter, the comparison gives useful clues as to the degree of contamination by telluric absorption. The bottom panel in Figure 2 shows the same spectral region in the bright ($V = 1.94$), early-type (B2 IV) star α Pavonis, observed on 1987 July 20 with the same instrumental set-up as the SN. This spectrum, also of very high S/N ($\simeq 2050$), provides a further check on atmospheric and detector-related features which may be affecting the [Fe x] region.

From Figures 2*a* and 2*b* it can be seen that telluric absorption makes a significant contribution to the red wing of the putative [Fe x] feature, since the absorption between $\lambda \simeq 6380.1$ and 6382.3 Å ($v_{\rm H} \simeq 265$–370 km s^{-1} in Fig. 1*b*) was considerably stronger on July 20, when all the other unblended telluric lines were also more prominent. An unidentified atmospheric line revealed by Hobbs' survey of this region, $\lambda 6381.11$ is likely to be one of the contributors. Although we cannot exclude the possibility that there may be some residual [Fe x] absorption at these velocities, we prefer to focus our analysis on the narrower, blue components of the candidate [Fe x] feature, which is evidently less affected by telluric absorption, as its strength and profile remained essentially unchanged between the two epochs.

Referring to the April 9 spectrum (Figs. 1*b* and 2*a*),[5] the feature under scrutiny is centred at $\lambda_{\rm OBS} \simeq 6379.67 \pm 0.02$ Å ($v_{\rm H} = 244$ km s^{-1} if [Fe x] $\lambda 6374.51$, given that at the time of

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[5] While the spectra obtained on all four epochs (see Table 1) are consistent with each other, we have found that there is little to be gained by adding all the data together and that it is more instructive to consider the spectra individually. This stems from the fact that the major source of uncertainty for [Fe x] absorption in the LMC is blending with telluric lines, whose strength changes from night to night. Similarly, as discussed below, the measurement of Galactic [Fe x] depends sensitively on the placement of the underlying SN continuum, which changed between the four epochs.

TABLE 2

TELLURIC LINES AND DIFFUSE INTERSTELLAR BANDS IN THE [Fe X] λ6375 SPECTRAL REGION

Line (1)	Origin (2)	W_λ[a] (mÅ) (4)	λ_{OBS}[a] (Å) (3)
Features *Not* Overlapping [Fe X] Absorption			
λ6361.252	⊕ (H_2O)	6361.26 ± 0.02[b]	1.8 ± 0.2[b]
λ6368.450	⊕ (H_2O)	6368.43 ± 0.02	1.8 ± 0.2
λ6368.93	⊕ (?)	...	≤0.7
λ6370.96	⊕ (?)	...	≤0.7
λλ6371.24, 6371.563 ...	⊕ (? + H_2O)	6371.45 ± 0.03	2.5 ± 0.3
λ6372.217	⊕ (H_2O)	...	≤0.7
DIB λ6376.08	Galactic ISM	6376.38 ± 0.03[c]	1.1 ± 02
λ6378.17	⊕ (?)	...	≤0.7
λ6382.549	⊕ (?)	6382.59 ± 0.04	1.1 ± 0.2
DIB λ6379.30	LMC ISM	6385.63 ± 0.05(:)	1.0 ± 0.2
Contaminants to [Fe X] Absorption[d]			
λ6373.42	⊕ (?)	6373.42 ± 0.03[e]	≤0.5
λ6379.273	⊕ (?)	6379.27 ± 0.03[f]	≤1.3
DIB λ6379.30	Galactic ISM	6379.60 ± 0.03[f,g]	≤4.3
λ6381.11	⊕ (?)	6381.11 ± 0.03[f]	≤1.1
DIB λ6376.08	LMC ISM	6382.05 ± 0.1[f,h]	≤0.6

[a] Measurements refer to 1987 April 9 spectrum.

[b] 1 σ errors due to photon statistics.

[c] $v_H = 15.8 \pm 0.1$ km s^{-1} ($v_H = v_{OBS} + 1.6$ km s^{-1} at the time of observation).

[d] Wavelengths and equivalent widths are estimated values on the basis of λ_{OBS} and W_λ of unblended lines (*see text*).

[e] Contaminating Galactic [Fe X] absorption.

[f] Contaminating LMC [Fe X] absorption.

[g] Adopting $v_H = 15.8 \pm 0.1$ km s^{-1} from DIB λ6376.08.

[h] Adopting $v_H = 282 \pm 5$ km s^{-1} from Vladilo *et al.* 1987.

observation $v_H = v_{OBS} + 1.6$ km s^{-1}) and extends from $\lambda_{OBS} \simeq$ 6379.0 to 6380.2 Å ($v_H \simeq$ 213–269 km s^{-1}) with an equivalent width $W_\lambda = 8.4 \pm 0.3$ mÅ. As can be seen from Table 2, we estimate that the telluric line λ6379.273 contributes at most 1.3 mÅ to this, while the Galactic DIB λ6379.30 is unlikely to account for more than a further 4.3 mÅ, leaving $W_\lambda \geq 2.5$ mÅ as a conservative lower limit for [Fe X] λ6374.51 absorption at LMC velocities. The maximum strength of λ6379.273 was estimated from the upper limits to the equivalent widths of the unblended telluric lines in the spectrum—which conform very well to their relative strengths as tabulated by Hobbs (1984*a*). The maximum contribution of DIB λ6379.30 was calculated from the measured upper limit of DIB λ6376.08 ($W_\lambda \leq 1.3$ mÅ, which in itself may overestimate the correction since the feature appears somewhat weaker in the July 20 spectrum) adopting a ratio $R = W_\lambda(\lambda6379)/W_\lambda(\lambda6376) \leq 3.3$ from the average value $R = 2.1 \pm 1.2$ in 30 stars observed by Herbig (1975) (this value is also consistent with the more limited set of measurements by Hobbs 1984*a*, 1985). The estimated upper limit W_λ (DIB λ6379.30) ≤ 4.3 mÅ is consistent with the nondetection of this feature toward R136a (Paper I); comparison with the data of Malaney and Clampin (1988) shows that the above value is indeed a conservative upper limit.

Finally, inspection of Figure 2*c* confirms that (*a*) we have not underestimated the strength of the telluric line λ6379.273 and (*b*) the feature we have detected is not an instrumental artifact, since the comparison star shows no comparable absorption in the spectral region in question. Of course, we cannot exclude altogether the possibility that the feature is a previously unrecognized interstellar line at Galactic velocities, given the unusually high S/N of our spectra. One such line, at λ = 6367.25 Å, was indeed encountered in the course of Hobbs' search for [Fe X] and originally mistaken for high-velocity [Fe X] absorption. We consider this interpretation unlikely, however, since in our earlier work (Paper I) we found no evidence for unidentified absorption near λ = 6379.7 Å in the spectra of two moderately reddened Galactic stars with values of $E(B-V)$ 2–3 times greater than $E(B-V) = 0.06$ appropriate to Galactic dust in the direction of SN 1987A (Fitzpatrick and Savage 1984). It is reasonable to expect that the strength of a weak unidentified interstellar line would generally correlate with colour excess, as found for example by Hobbs (1985) for λ = 6367.25 Å. Furthermore, Hobbs' (1988, private communication) spectra of ζ Oph and HD 190603 [$E(B-V) = 0.32$ and 0.72, respectively] also show no absorption near λ = 6379.7 Å.

We therefore conclude that we have detected [Fe X] λ6374.51 absorption due to the interstellar medium of the LMC, with an equivalent width of at least 2.5 mÅ.

b) *Coronal Gas in the LMC*

Even such a low value of W_λ implies a high column density of coronal gas in front of SN 1987A, because of the intrinsic weakness of [Fe X] λ6375. Following the reasoning of Paper I, $W_\lambda \geq 2.5$ mÅ implies a column density $N(\mathrm{Fe}^{9+}) \geq 3.3 \times 10^{16}$ cm^{-2}, if we adopt $f = 2.1 \times 10^{-7}$ for the transition (Hobbs 1984*b* and references therein). This in turn implies $N(\mathrm{Fe}) \geq 1.3 \times 10^{17}$ cm^{-2} for all Fe ion stages, since in collisional ionization $\mathrm{Fe}^{9+}/\mathrm{Fe} \leq 0.26$, the peak in the fractional abundance occurring at $T \simeq 1.25 \times 10^6$ K (Shull and Van Steenberg 1982). If we further assume a solar abundance of Fe [$(\mathrm{Fe/H})_\odot = 3.9 \times 10^{-5}$; Aller 1987], the total column density of highly ionized gas must then be in excess of $N(\mathrm{H})_{\mathrm{HIM}} \geq 3.2 \times 10^{21}$ cm^{-2}. $N(\mathrm{H})_{\mathrm{HIM}}$ could well be several times this value, particularly if $T \neq 1.25 \times 10^6$ K and if the Fe abundance of the LMC interstellar medium is less than solar, as found in LMC stars (log $[(\mathrm{Fe/H})_{\mathrm{LMC}}/(\mathrm{Fe/H})_\odot] \simeq -0.2$; Russell, Bessell, and Dopita 1988). In any case, it is difficult to escape the conclusion that the column density of 10^6 K gas toward SN 1987A is comparable to, or exceeds, that of neutral gas: $N(\mathrm{H\ I}) = 2.75 \times 10^{21}$ cm^{-2} from the 21 cm emission measurements by Wayte (1988). Before discussing the implications of these results, we consider briefly [Fe X] absorption from interstellar gas in our Galaxy.

c) *Galactic* [Fe X] *Absorption*

As can be seen from Figures 1 and 2, the counts recorded are consistently below the continuum level at wavelengths appropriate to [Fe X] absorption in the Milky Way. A broad and shallow feature may be present between $\lambda_{OBS} \simeq 6372.7$ and 6375.9 Å ($v_H \simeq -85$ to $+65$ km s^{-1}), averaging less than a 0.2% drop in intensity relative to the continuum, and with $W_\lambda = 5.3 \pm 0.6$ mÅ. The contribution from the telluric line λ6373.42 is unlikely to exceed $W_\lambda = 0.5$ mÅ (Table 2). It is intriguing that the width and profile of this feature are as expected for absorption produced by the naturally turbulent hot component (HIM) in the McKee and Ostriker (1977) model of the ISM. Despite this, and despite the fact that the feature appears to be present in both spectra with the highest S/N (see Figs. 2*a* and 2*b*), it is evident that its reality depends critically on the exact continuum placement (unlike the [Fe X] absorption at LMC velocities); we therefore do not feel justified in claiming a positive detection.

A clear indication of the difficulty of the measurements attempted here is obtained when we consider that, were the feature real, its strength would imply a density of 10^6 K gas in the disk and halo of the Galaxy far in excess of current estimates, as we now show. Edgar and Chevalier (1986) have calculated the column densities of highly ionized species dominant at $T \simeq 10^5$ K in a model for a hot Galactic corona cooling from $T > 10^6$ K and obtained a good match to the values measured from *IUE* data. However, their prediction of $N(\mathrm{Fe}^{9+}) \leq 6 \times 10^{14}$ cm^{-2} along a line of sight perpendicular to the Galactic plane, is ~ 60 times lower than $N(\mathrm{Fe}^{9+})|\sin b| = 3.7 \times 10^{16}$ cm^{-2} implied by the present results, if the Galactic [Fe x] feature were real. Similarly, the corresponding $N(\mathrm{H})_{\mathrm{HIM}}$ exceeds by two orders of magnitude the value expected if the disk HIM of the McKee and Ostriker model extended into the halo with a scale height $h \simeq 5$ kpc. Furthermore, if the column density of 10^6 K gas implied by the [Fe x] absorption were typical of the Galaxy, the corresponding mass in the hot phase of the ISM would be $\approx 4 \times 10^{10}$ $M_\odot$! While such large discrepancies from current estimates make the reality of the supposed [Fe x] feature even more unlikely, the present observations provide an incentive for further attempts to measure the column density of coronal gas in the Galactic halo. We return to this point in § V below.

IV. DISCUSSION

Returning to [Fe x] in the LMC, it is of considerable interest to establish the origin of the highly ionized gas we have detected. One possibility is that the [Fe x] absorption traces a widely distributed hot component of the ISM of the LMC, analogous to the highly ionized medium of the McKee and Ostriker three-phase model of the Galactic ISM. Alternatively, the detection of [Fe x] along this particular sight-line may be more closely related to SN 1987A itself, and may be due to ionization by the explosive event of circumstellar or interstellar material in the vicinity of the SN. The large column density indicated by our observations [$N(\mathrm{H}) \geq 3.2 \times 10^{21}$ cm^{-2}; § III*b* above] favors the former interpretation, as we now discuss.

a) *Circumstellar Origin*

First of all, it is easy to show that circumstellar material ejected by Sk $-69°202$, the B3 Ia progenitor of SN 1987A, fails by several orders of magnitude to account for the [Fe x] detection. The estimates by Renzini (1987) for the mass-loss parameters at different stages in the evolution of the progenitor (from the compilation by Chiosi and Maeder 1986), indicate that most of the mass loss takes place during the red supergiant phase when ≈ 10 $M_\odot$ are ejected into a volume ≈ 10 pc in radius from the star; the corresponding column density through the shell is only $N(\mathrm{H}) \approx 10^{18}$ cm^{-2}. In the case of Sk $-69°202$, the inner region of the red supergiant wind was subsequently acted upon by the faster wind in the blue supergiant phase, presumably giving rise to a dense shell of shocked gas. From a detailed consideration of the properties of the wind interaction region and its effect on the circumstellar medium Chevalier (1987) estimated $N(\mathrm{H}) \simeq (0.3 - 10) \times 10^{19}$ cm^{-2}. Observations of the UV and optical emission lines produced as gas in the shell recombines following ionization in the supernova explosion (Fransson *et al.* 1989; Wampler and Richichi 1988) indicate $N(\mathrm{H}) \approx 6 \times 10^{18}$ cm^{-2}, more than 500 times smaller than the column density of ionized gas traced by the [Fe x].

b) *Interstellar Gas Ionized by SN 1987A*

A column density as high as $N(\mathrm{H}) \geq 3.2 \times 10^{21}$ cm^{-2} could still, in principle, be due to a dense interstellar cloud located in front of the SN and ionized by the X-ray flash thought to accompany the emergence of the shock from the stellar photosphere (e.g., Klein and Chevalier 1978; Lasher and Chan 1979). The properties of this burst are poorly known; the model calculations by Klein and Chevalier suggest that in the energy range of interest here (0.2–0.5 keV, since the ionization potential of Fe^{8+} is 235 eV) a mean peak luminosity $L_x \sim 1 \times 10^{44}$ ergs s^{-1} for a period $t \sim 30$ min with a mean photon energy $h\nu \sim 0.3$ keV may be representative estimates. With these values, the total number of soft X-ray photons emitted at shock breakout is

$$\frac{L_x t}{h\nu} \equiv \Phi_0 t \simeq 4 \times 10^{56} . \tag{1}$$

This is in fact likely to be an overestimate, as SN 1987A is generally thought to have had only a feeble flash (Dopita *et al.* 1987; Fransson *et al.* 1987; Chevalier 1987; Edwards 1987) due to the small radius of the progenitor (compared with that of a red supergiant, the canonical precursor of type II supernovae). The brightness and spectral slope of the ultraviolet light echo observed with *IUE* (Gilmozzi *et al.* 1988) appear to confirm this point.

The X-ray flux will ionize matter over a volume

$$\frac{4}{3}\pi r^3 = \frac{\Phi_0 t}{n_{\mathrm{H}}} , \tag{2}$$

where r is the distance from the SN and n_{H} the volume density of the ambient interstellar gas. The corresponding column density of ionized gas in line to the SN is given by

$$N_{\mathrm{H}} = n_{\mathrm{H}} r = \left(\frac{3}{4\pi} \Phi_0 t n_{\mathrm{H}}^2\right)^{1/3} \tag{3}$$

or

$$n_{\mathrm{H}}^2 = \frac{4\pi}{3} \frac{N_{\mathrm{H}}^3}{\Phi_0 t} . \tag{4}$$

Substituting $\Phi_0 t \simeq 4 \times 10^{56}$ and $N_{\mathrm{H}} \geq 3.2 \times 10^{21}$ cm^{-2} in equation (4), we obtain

$$n_{\mathrm{H}} \geq 2 \times 10^4 \text{ cm}^{-3} \tag{5}$$

and

$$r \leq 0.05 \text{ pc} . \tag{6}$$

A weaker X-ray flash would require even higher volume densities to produce the observed column density of coronal gas, as can be seen from equation (4).

In other words, if the [Fe x] we detect was produced by the X-ray flash of SN 1987A, it must arise in a dense interstellar cloud close to the SN. The high density implied is not in itself implausible. For example, Morton (1975) deduced $n_{\mathrm{H}} = 10^4$–10^5 cm^{-3} for the cloud near ζ Oph, where $N(\mathrm{H}) = 1.4 \times 10^{21}$ cm^{-2}; these values are similar to those being considered here. However, if gas with $n_{\mathrm{H}} \geq 2 \times 10^4$ cm^{-3} were highly ionized by a pulse of X-ray radiation, it would recombine in a short time. Quantitatively, from the expressions by Shull and Van Steenberg (1982) for the radiative and dielectronic recombination coefficients to form Fe^{8+} at

$T = 20{,}000$ K (to take into account some heating of the cloud by the X-ray burst), we deduce a recombination time

$$t_{\rm rec} = 2.2 \times 10^6 n_4^{-1}\ {\rm s}\ , \qquad (7)$$

where n_4 is the cloud density in units of 10^4 cm^{-3}. Thus, we would expect all the Fe^{9+} to have recombined less than ~12 days after the X-ray flash. As our observations were obtained over a period of nearly 5 months and no obvious variations were seen in the strength of the [Fe x] absorption between the different epochs (compare Figs. 2*a* and 2*b*), we conclude that an origin in circumstellar gas photoionized by the SN appears unlikely.

c) Million-Degree Gas in 30 Doradus

We are thus drawn to the alternative interpretation that the [Fe x] absorption may trace more widespread coronal gas in the interstellar medium of the LMC. In our view, this is the most plausible explanation, given the exceptional environment in which SN 1987A occurred. The SN is only ~20′ (= 273 pc) to the SW of the supergiant H II region 30 Doradus, the largest concentration of young, massive stars in the Local Group of galaxies (Kennicutt 1984), and the region with the highest density of supernova remnants in the LMC (Long, Helfand, and Grabelsky 1981; Mills *et al.* 1984; Meaburn 1988). Furthermore, 30 Doradus itself appears to be only the most conspicuous component—at optical wavelengths—of a much larger complex of recent and on-going star formation, on a scale of ~2 kpc (Walborn 1984). It is now recognised (e.g., McCray and Kafatos 1987) that the combined effects of supernovae from clusters of massive stars can lead to the formation of huge cavities in interstellar space, where the interstellar gas has been swept-up into expanding "supershells" with radii greater than 100 pc. Indeed, between six and nine such structures, with radii of 300–900 pc, are known to exist in the LMC (Meaburn 1980; Dopita, Mathewson, and Ford 1985); two of these appear to be related to the 30 Doradus nebula.

SN 1987A itself is seen projected onto a region of complex emission-line structure (D'Odorico 1987), close to the edge of a large bubble, 50–60 pc in radius, which is a source of radio, optical, and X-ray emission (Mathewson *et al.* 1985; Lortet and Testor 1984). Furthermore, the properties of the light echoes around SN 1987A (Chevalier and Emmering 1988; Pettini 1988; Gilmozzi *et al.* 1988) indicate that the major concentrations of LMC interstellar dust in line of sight are in the form of thin sheets located ~115 and ~315 pc in front of the SN. This is consistent with the notion that the SN exploded behind—or inside—a cavity which had already been evacuated of most interstellar dust. The recently discovered eccentricity of the outer ring of the light echo suggests that the cavity may be centred on 30 Doradus (Allen, Couch, and Malin 1988).

The interior of such "superbubbles" is likely to be filled with 10^6 K gas, produced from conductive evaporation from the inner surface of the shell; this plasma is an obvious candidate for the site of the [Fe x] absorption we detect. This interpretation is further supported by the good agreement between the central velocity of the absorption feature, $v_{\rm H} = 244$ km s^{-1}, and that of the expanding H II region, $v_{\rm H} \simeq 250$ km s^{-1}, as determined from radio, optical, and ultraviolet observations of the core of 30 Doradus (de Boer, Koornneef, and Savage 1980 and references therein). Nevertheless, the column density of ionized gas implied by the [Fe x] detection is remarkably high, and we now consider some of its implications.

i) *Other Highly Ionized Species*

Since the column density of gas at a given temperature varies across a conductive interface approximately in proportion to $T^{2.05}$ (McKee and Cowie 1977), we can predict the column densities of other ions whose abundances peak at temperatures lower than $T = 10^6$ K, as described in Paper I. Specifically, if $N({\rm Fe}^{9+}) \simeq 3.3 \times 10^{16}$ cm^{-2} (§ III*b*), we would expect a corresponding $N({\rm C}^{3+}) \simeq 2.9 \times 10^{15}$ cm^{-2}, given that C^{3+} is most abundant at $T = 1 \times 10^5$ K (where C^{3+}/C = 0.34; Shull and Van Steenberg 1982) and adopting a solar C/Fe ratio (= 11.8; Aller 1987). This is probably an overestimate, since C appears to be deficient by a factor of ~5 relative to Fe in the LMC (Russell, Bessell, and Dopita 1988). In any case, the above value is consistent with the strongly saturated interstellar C IV lines observed in *IUE* spectra of the SN, indicating $N({\rm C}^{3+}) \gg 3 \times 10^{14}$ cm^{-2} (Blades *et al.* 1988; Savage *et al.* 1989).

ii) *Energetic Considerations*

It would clearly be of interest to know the extent of the coronal gas detected. If the column density $N({\rm H})_{\rm HIM} \geq 3.2 \times 10^{21}$ cm^{-2} derived above is typical of a region ~1 kpc in size, the average volume density of the gas is:

$$n_{\rm HIM} = \frac{N({\rm H\ I})_{\rm HIM}}{2R} \geq 0.52\left(\frac{R}{1\ {\rm kpc}}\right)^{-1}\ {\rm cm}^{-3}\ , \qquad (8)$$

where R is the radius of the region filled with 10^6 K gas, and the corresponding pressure, assuming $T = 1.25 \times 10^6$ K, is

$$\frac{p}{k} = 2.3nT \geq 1.5 \times 10^6\left(\frac{R}{1\ {\rm kpc}}\right)^{-1}\ {\rm cm}^{-3}\ {\rm K}\ . \qquad (9)$$

Such overpressure may not be unreasonable for a superbubble; indeed surveys of interstellar pressures, as measured by the relative populations of the fine-structure levels of C I, do show interstellar clouds with values of $p/k > 10^5$, particularly in the vicinity of young supernova remnants (Jenkins and Shaya 1979; Jenkins, Jura, and Loewenstein 1983; Jenkins, Wallerstein, and Silk 1984).

The emissivity of the gas as it cools would be considerable, $N({\rm H})_{\rm HIM} \geq 3.2 \times 10^{21}$ cm^{-2} implying an emission measure:

$${\rm EM} \geq 5.4 \times 10^2\left(\frac{R}{1\ {\rm kpc}}\right)^{-1}\ {\rm cm}^{-6}\ {\rm pc}\ . \qquad (10)$$

This radiation would be emitted chiefly as soft X-rays ($h\nu \simeq 0.1$ keV). The deep *HEAO 1* A2 map of the LMC by Singh *et al.* (1987)—most sensitive at 0.25 keV—shows that the observed X-ray emission falls short of this limit by three to four orders of magnitude, depending on the temperature of the gas and the extent of the emitting region. The large-scale survey in the C band (0.1–0.28 keV) with the *SAS 3* satellite by Marshall and Clark (1984) leads to a similar discrepancy. However, it may still be possible to reconcile the X-ray data with the [Fe x] observations if the hot plasma is located *behind* the neutral gas in 30 Doradus, as proposed by de Boer, Koornneef, and Savage (1980). The high column densities of H I in this direction [$N({\rm H}) > 1 \times 10^{21}$ cm^{-2}; McGee, Newton, and Morton 1983] would be very effective in absorbing soft X-rays.

An independent constraint is provided by the recent rocket observations of SN 1987A in the far-UV by Shull *et al.* (1988, private communication). These data, which at the time of writing are still being analyzed, apparently place a limit of $\leq 2.5 \times 10^5$ photons cm^{-2} s^{-1} str^{-1} to O VI $\lambda\lambda$1032, 1038 emission in the direction of the supernova. For a gas at $T = 3 \times 10^5$ K, at which the fractional abundance of O^{5+} is highest, Jakobsen and Paresce (1981) estimate that the above flux corresponds to an emission measure $EM \leq 2.5$ cm^{-6} pc. While this value is somewhat uncertain (Jakobsen and Paresce (1981) calculations are only accurate to within one order of magnitude), and even allowing for the fact that, at the resolution of the rocket data by Shull *et al.*, some of the O VI emission is likely to be suppressed by the nearby strong Lyman β and H_2 absorption, the discrepancy of ≥ 2 orders of magnitude between the UV results and the emission measure implied by the [Fe x] detection is a cause for concern. Possibly the gas is mostly at temperatures greater than 3×10^5 K, where the fractional abundance of O^{5+} is reduced (at $T = 1.25 \times 10^6$ K, where Fe^{9+} is most abundant, the relative fraction of O^{5+} is ~ 2 orders of magnitude lower than at $T = 3 \times 10^5$ K; Shull and van Steenberg 1982). In summary, neither the soft X-ray nor the far-UV data show the emission expected from the high densities of coronal gas indicated by the [Fe x] absorption, although neither wavelength band is well suited to detecting gas at the temperatures traced by [Fe x]. Firm conclusions on this point will require better data, particularly on the X-ray emission, and improved modelling of the emission properties of the region.

Finally, we consider the energy loss through cooling. Adopting a cooling rate $\Lambda/n_{\rm HIM}^2 \simeq 1.5 \times 10^{-22}$ ergs cm^3 s^{-1} at $T = 1.25 \times 10^6$ K (Gaetz and Salpeter 1983),[6] leads to a total power radiated from the superbubble:

$$P \geq 4.7 \times 10^{42} \left(\frac{R}{1\ \rm kpc}\right) \rm ergs\ s^{-1} \tag{11}$$

and a corresponding mass of coronal gas:

$$M_{\rm HIM} \geq 5.3 \times 10^7 \left(\frac{R}{1\ \rm kpc}\right)^2 M_\odot\ . \tag{12}$$

These are extremely high values if the coronal gas is distributed over a scale of ~ 1 kpc. For example, to balance the energy loss through cooling would require a SN rate

$$r_{\rm SN} \geq 15(100\ {\rm yr})^{-1} \left(\frac{R}{1\ \rm kpc}\right) \tag{13}$$

assuming that each supernova deposits $\sim 10^{51}$ ergs of kinetic energy in the hot medium. This is one order of magnitude greater than the rate at which radio SNRs are produced in the LMC (Mills *et al.* 1984). Although many supernovae may not give rise to obvious remnants if they explode in cavities already evacuated by previous energetic events (McCray and Kafatos 1987), such a high rate seems nevertheless excessive. On the other hand, if $R \simeq 100$ pc [and $N(H)_{\rm HIM}$ has not been underestimated by a large factor], it may be just possible for the coronal gas to be maintained against radiative losses and its total mass would then be comparable to the mass of ionized gas in 30 Doradus emitting at Hα ($\simeq 6 \times 10^5\ M_\odot$; Kennicutt 1984) and only $\sim 4\%$ of the mass of neutral gas detected in 21 cm emission ($\simeq 1.4 \times 10^7\ M_\odot$; McGee and Milton 1966).

V. CONCLUDING REMARKS AND SUGGESTIONS FOR FUTURE WORK

The exceptional brightness of SN 1987A, a rare event on a human time scale, provided astronomers with the means to study the interstellar medium toward the Large Magellanic Cloud in greater detail and with higher accuracy than ever before. The detection of [Fe x] absorption reported here is yet another notable "first" for SN 1987A, fulfilling sooner than expected the prediction by Jenkins (1984, 1987) that coronal gas may one day be observable at optical wavelengths. Yet, the discussion of our results leads to the conclusion that the detection of [Fe x] owes much to the fact that SN 1987A occurred in a region where supernovae are unusually *frequent* events which, by their combined effects, can maintain substantial densities of highly ionized gas.

If this interpretation is correct, it should be possible to detect comparable [Fe x] absorption toward R136a and other bright sources in 30 Doradus with only a moderate observing effort, the current measurement being only a factor ~ 2 lower than the 3 σ limit reached in Paper I. Furthermore, the spectra of luminous early-type stars are likely to provide more uniform continua than the SN in the region of interest, allowing a renewed search for [Fe x] in the Galactic halo. Attempts to improve on the present limit by repeated observations of the SN have proved ineffective; since 1987 September, with SN 1987A well into the nebular phase, the spectrum has developed sufficient intrinsic structure to make the determination of the continuum and the identification of weak interstellar lines progressively more difficult and subjective (Stathakis, Dopita, and Cannon 1989).

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[6] In the temperature regime of interest, line radiation from Fe ions is the main cooling mechanism; thus we may have overestimated the cooling function if Fe is less abundant in the LMC than in the Sun. However, the net result would be to *increase* the values of P and $M_{\rm HIM}$ in eqs. (11) and (12) by a corresponding amount, because a lower Fe abundance would imply higher values of $N(H)_{\rm HIM}$ (§ IIIb) and therefore $n_{\rm HIM}$. The latter contributes quadratically to the cooling rate.

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