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Na I INTERSTELLAR ABSORPTION IN THE DIRECTION OF TWO LMC SUPERGIANTS IN THE FIELD OF SN 1987A[1]

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ABSTRACT

Observations of Na I interstellar lines of the two LMC supergiants Sk $-69°203$ and Sk $-69°211$, at few arcminutes from the SN 1987A, have been obtained with the ESO CES spectrograph linked by fibers to the 3.6 m telescope at La Silla, Chile. Remarkable differences are found among the three contiguous lines of sight. The Galactic components have different strengths implying strong dishomogeneities of the interstellar gas of the Galactic disk on a scale of tenths of parsecs. The component of $V_{\rm HEL} \simeq 64$ km s^{-1} is much stronger toward Sk $-69°211$ than toward SN 1987A and is almost absent in Sk $-69°203$. The SN 1987A features at $V_{\rm HEL} \simeq 216$ km s^{-1}, 253 km s^{-1}, and 269 km s^{-1} are absent from the spectra of the two supergiants and appear as a characteristic signature of the supernova line of sight. Finally, the main LMC absorption shows variations in strength and radial velocity between each pair of the three lines of sight, suggesting a complex distribution of the main body of the LMC IS gas in the direction of the supernova.

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

I. INTRODUCTION

In the last few years, the line of sight to the LMC has been the object of extensive studies in the ultraviolet (Savage and de Boer 1979, 1981; de Boer and Savage 1980) and visual (Blades 1980; Walborn 1980; Blades and Meaburn 1980; Songaila and York 1980; Songaila *et al.* 1986), revealing an unusually rich interstellar (IS) spectrum. However, observations at high dispersion ($RP \geq 30{,}000$) have been limited to a few bright stars. The region of the Na I D_1 and D_2 lines, in particular, has been observed in R136, the central object of 30 Dor (Dekker *et al.* 1986), and in the three supergiants R126, R127, and R116 (Ferlet, Dennefeld, and Maurice 1985). The appearance of the SN 1987A provided a new, exceptionally bright background source, and a high number of IS clouds were detected and studied in detail (Vidal-Madjar *et al.* 1987; de Boer *et al.* 1987; Blades *et al.* 1988*a*, *b*).

In this *Letter* we present high-resolution (FWHM ≈ 5 km s^{-1}) and high S/N observations of the Na I region of two additional faint LMC supergiants, Sk $-69°203$ and Sk $-69°211$, which are located (Table 1) at 2'.2 and 8'.5 from the SN 1987A progenitor (Sk $-69°202$), respectively. These angular distances correspond to 32 pc and 134 pc at a LMC distance of 50 kpc.

II. OBSERVATIONS AND DATA REDUCTION

The observations were performed in 1988 March at ESO, La Silla, using the CES with the short camera (f/2.5) and a CCD detector (Dekker *et al.* 1986). The spectrograph was fed with a 40 m long optical fiber from the Cassegrain focus of the 3.6 m telescope. The instrumental setup is given in detail in Avila and D'Odorico (1988). The spectra were extracted, flat-fielded, calibrated in wavelength, and smoothed using standard commands of IHAP, the ESO image processing system. A Na I spectrum of the star α Pic was used as a template to eliminate the telluric contamination. The rms around the continuum region 5885.5–5889.5 Å is $\sigma = 0.0189$ (S/N $\simeq 53$) and $\sigma = 0.0152$ (S/N $\simeq 66$), for Sk $-69°203$ and Sk $-69°211$, respectively. The spectral resolution estimated from the FWHMs of sharp telluric lines is $\delta\lambda = 106$ mÅ, i.e., $RP = \lambda/\delta\lambda \simeq 5.6 \times 10^4$. The minimum detectable equivalent width, $\mathrm{EW}_{\min} = 3\sigma_{\rm cont}\,\delta\lambda$, is therefore 5.9 mÅ and 4.8 mÅ for Sk $-69°203$ and Sk $-69°211$, respectively. These figures also give an estimate of the observational errors in the EWs. The IS absorptions toward SN 1987A were analyzed using a Reticon spectrum taken by us with the CAT+CES at ESO, La Silla. After an analogous data reduction, this spectrum was rebinned at the same wavelength step employed for the two CCD spectra. For this spectrum we obtain $\sigma_{\rm cont} = 0.00592$, $\delta\lambda = 83$ mÅ ($RP \simeq 7.1 \times 10^4$), and $\mathrm{EW}_{\min} = 1.5$ mÅ. In Figures 1 and 2 we compare the spectra of the two supergiants with the spectrum of SN 1987A. All the Na I components detected in the spectra are identified in Table 2.

III. GALACTIC GAS

Two components at $V_{\rm HEL} \simeq 10$ km s^{-1} and at $V_{\rm HEL} \simeq 24$ km s^{-1} are clearly present in both stars, as well as a third and weaker component at $V_{\rm HEL} \simeq 19$ km s^{-1} which is not fully resolved from the 24 km s^{-1} component.

The component at 10 km s^{-1} is also present in SN 1987A and can be related to the absorptions at $V_{\rm HEL} \simeq 10$ and $\simeq 11$ km s^{-1} found by Ferlet, Dennefeld, and Maurice (1985) toward R127 and R128, respectively. This component could be interpreted in terms of the local "interstellar wind" discovered by Crutcher (1982) within a volume of a few hundred parsecs from the Sun. The expected velocity of this gas in the direction of the LMC deduced from Crutcher relation is in fact $V_{\rm HEL} \simeq 9$ km s^{-1}. As can be seen from the figures, there are significant differences in the line strengths of the 10 km s^{-1} component. The

[1] Based on observations collected at the European Southern Observatory, La Silla, Chile.

TABLE 1

OBSERVATIONAL DATA

Star	V	Spectral Type	$B-V$	R.A.	Decl.
Sk −69°203.......	12.29	B0.5	0.01	5^h36^m	−69°16′
Sk −69°211.......	10.36	B8 I	0.09	5 36	−69 26
Sk −69°202.......	12.20	B3 I	0.04	5 36	−69 19

NOTE.—Data from Rousseau *et al.* 1978.

strongest absorption is seen toward Sk 69 203, where the Na I column density is 2.8 and 1.4 higher than the column densities observed toward Sk 69 211 and SN 1987A, respectively. Since 1′ corresponds to 0.03 pc at a distance of 100 pc, our observations give one of the smallest linear scales (<0.1 pc) on which strong density variations in the ISM have been detected so far. Variations in the strength of IS absorptions on comparable or smaller scales have been found toward the globular cluster M22 (Cohen 1981) and the visual binary system HD 72127 (Hobbs, Wallerstein, and Hu 1982).

The component of $V_{HEL} \simeq 24$–26 km s^{-1} is generally the strongest one among the galactic absorptions and is also present in the spectra of SN 1987A, R136, R116, R127, and R128. In our spectra the lines are strongly saturated, and the deduced column densities are quite uncertain.

IV. THE 64 km s^{-1} CLOUD

Sk −69°211, and possibly Sk −69°203, show a component at the intermediate velocity of $V_{HEL} \simeq 64$ km s^{-1}, identified by Vidal-Madjar *et al.* (1987) in SN 1987A. When compared to the SN 1987A, the 64 km s^{-1} feature is weaker in Sk −69°203, but about 5 times stronger toward Sk −69°211, where N(Na I) = 3.1×10^{11} cm^{-2}. Due to the perfect velocity correspondence, the 64 km s^{-1} component is almost certainly the same cloud as that detected toward R127 and R128 by Ferlet, Dennefeld, and Maurice (1985), who derived N(Na I) = 1.6×10^{11} cm^{-2} and 0.94×10^{11} cm^{-2}, respectively. It thus appears that the line of sight toward Sk −69°211 is the closest to the core of the cloud.

The location of the intermediate velocity clouds is not easily identified. Features at $V_{LSR} \simeq 60$ km s^{-1} and $V_{LSR} \simeq 120$ km s^{-1} ($V_{HEL} = V_{LSR} + 15.2$ km s^{-1}) were discovered by Savage and de Boer (1981) by means of *IUE* observations of LMC supergiants and assigned by them to material surrounding the Galactic halo. Recently a different claim has been advanced by Songaila *et al.* (1986) who found evidence that the intermediate-velocity gas is located in sheets within the two Clouds. The McGee and Newton (1986) 21 cm measurements at R.A. = 5^h39^m and decl. = −69°30′, reveal a H I component at $V_{HEL} \simeq 60$ km s^{-1}, which can be associated with this cloud. Combining the hydrogen column density estimated from these authors, N(H I) = 7.1×10^{18} cm^{-2}, with our value of N(Na I) toward Sk −69°211 we obtain N(Na I)/N(H I) = 4.3×10^{-8}. This ratio is 1.1 dex higher than the average value of N(Na I)/N(H) = 3.4×10^{-9} found by Albert (1983) in the Galactic disk. This could indicate a lower depletion of Na, which is a particular signature of halo high-velocity gas. The same conclusion is arrived at by Blades *et al.* (1988*b*), who, by using *IUE* data, derived abundances close to the solar ones for this cloud. Another indication for a halo origin of this cloud comes from the comparison with the Na I observations of R127 and R128 by Ferlet, Dennefeld, and Maurice (1985). These stars are LMC members, and they exhibit the feature at 64 km s^{-1}, but they do not show evidence of the LMC gas, indicating that the 64 km s^{-1} component cannot be associated with the LMC gas.

V. LMC GAS

The radial velocities of the two stars, derived from the centroid of the He I line at 5875.6 Å, are $V_{HEL} \simeq 275$ km s^{-1} (Sk −69°211) and $V_{HEL} \simeq 316$ km s^{-1} (Sk −69°203), confirming their LMC membership. In the IS spectra of Sk −69°203 and Sk −69°211 there is only one strong LMC absorption at $V_{HEL} \simeq 277$ km s^{-1} and $\simeq 299$ km s^{-1}, respectively, while in the SN 1987A spectrum the main absorption is found at $V_{HEL} \simeq 280$ km s^{-1}. The column density of the main LMC absorption toward SN 1987A is about 4 times higher than toward Sk −69°203 and about twice the value derived for

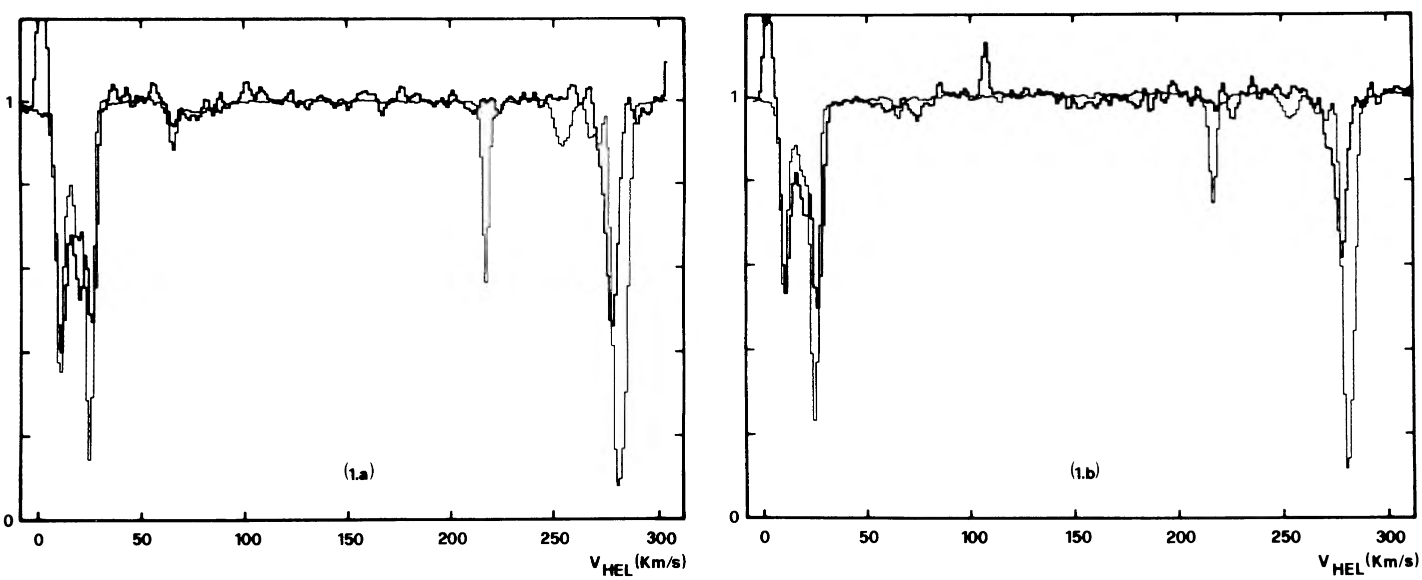

FIG. 1.—Interstellar Na I D_2 (*a*) and D_1 (*b*) absorption components toward Sk −69°203 (*thick line*) and SN 1987A (*thin line*). Velocities are heliocentric. The emissions at rest velocity are due to atmospheric Na I.

TABLE 2

INTERSTELLAR Na I COMPONENTS

D2			D1				
λ_{obs} (Å)	RV (km s^{-1})	EW (mÅ)	λ_{obs} (Å)	RV (km s^{-1})	EW (mÅ)	N(Na I) (10^{11} cm^2)	b (km s^{-1})
			Sk −69°203				
5890.15	10.2	70	5896.13	10.2	49	7.5	1.6
5890.32	18.8	73	5896.29	18.7	40	4.3	4.9
5890.46	25.7	55	5896.43	25.8	52	18.7:	0.9[a]
5891.22	64.4	4:	...[b]	...[b]	...[b]	0.2:	(L)[c]
5891.40	73.7	14	5897.36	73.3	6:	0.7	(L)[c]
5895.39	276.8	86	5901.37	277.0	58	8.3	2.0
			Sk −69°211				
5890.13	9.3	46	5896.11	9.3	25	2.7	3.7
5890.31	18.0	44	5896.27	17.7	17	2.0:	(L)[c]
5890.44	25.1	59	5896.42	25.1	49	13.1:	0.9
5891.21	64.0	42	5897.18	64.0	25	3.1	1.5
5894.08	210.3	8	...[b]	...[b]	...[b]	0.38	(L)[c]
5895.82	298.9	74	5901.80	298.9	62	17.4	1.2
			SN 1987A				
5890.14	9.5	60	5896.11	9.5	39	5.3	1.5
5890.31	18.5	56	5896.30	19.0	34	4.2	1.8
5890.43	24.3	66	5896.40	24.4	59	31.5:	0.9
5891.22	64.5	9	5897.19	64.6	6	0.5	(L)[c]
5894.20	216.3	34	5900.18	216.4	22	2.8	1.0
5894.92	253.2	18	5900.90	253.3	10	1.0	1.5
5895.19	266.7	14	5901.16	266.6	8	0.69	(L)[c]
5895.47	281.0	151	5901.44	280.9	125	33.4	2.4

[a] Value estimated on the basis of the b value derived for the same component in the other two lines of sight.

[b] Undetected.

[c] Linear part of the curve of growth.

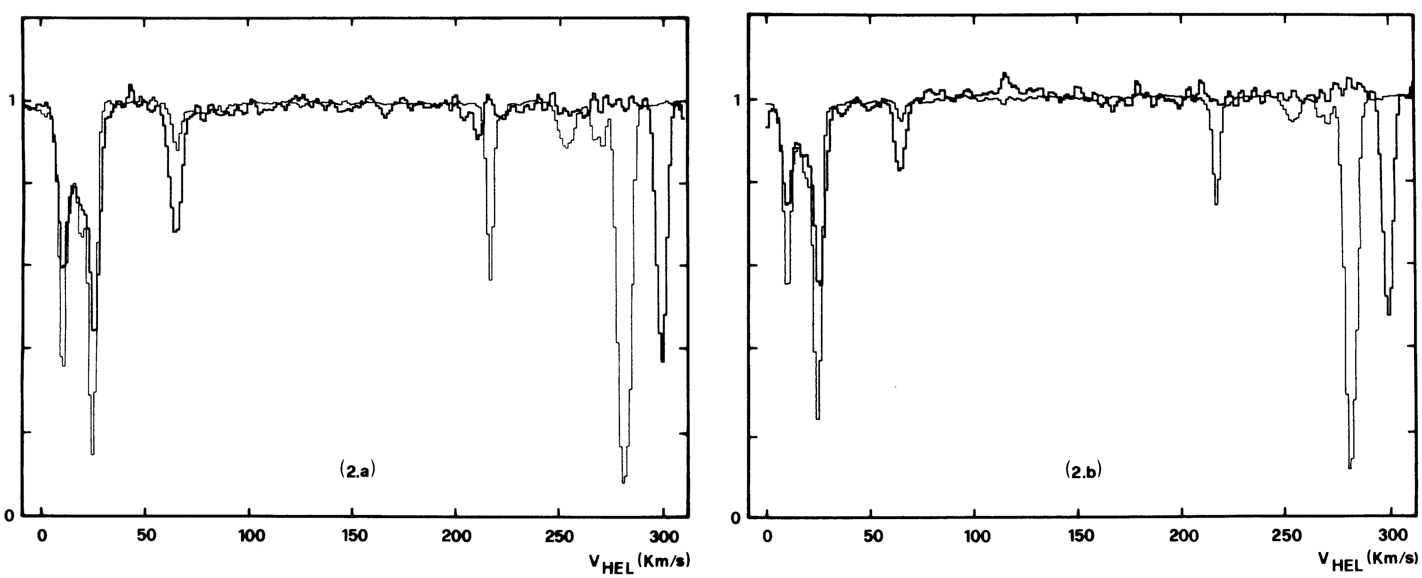

FIG. 2.—Interstellar Na I D_2 (*a*) and D_1 (*b*) absorption components toward Sk −69°211 (*thick line*) and SN 1987A (*thin line*). Velocities are heliocentric.

Sk −69°211. Thus SN 1987A appears to be located beyond the two Sanduleak stars.

Other smaller components are present in the SN 1987A spectrum at $V_{\rm HEL} \simeq 216$ km s^{-1}, 253 km s^{-1}, and 269 km s^{-1}, but no trace of these components, whose strength is well above our detection limit, is found in the two supergiants. The component at 216 km s^{-1} is perhaps seen in the spectrum of Sk −69°211, where there is a small feature at $V_{\rm HEL} \simeq 210$ km s^{-1} visible only in the D_2 line and just above the noise level (EW = 8 mÅ). The absence of the weaker features in the two supergiants suggests that the corresponding components arise deep inside the LMC. The determination of the precise location of the gas producing the LMC components is complicated by the fact that the large-scale structure of the gas in the LMC is not clearly established. From a 21 cm survey of the LMC, McGee and Milton (1966) advanced the hypothesis that the main body of the LMC gas is contained in three large overlapping sheets of gas centered on radial velocities 243 km s^{-1}, 273 km s^{-1}, and 300 km s^{-1}. Such a structure is confirmed by the more recent works of Meaburn *et al.* (1987) and McGee and Newton (1986). Inspection of the sensitive 21 cm observations by Meaburn *et al.* (1987) in the region within about 1° (≈1 kpc) from the supernova reveals emission components at velocities very close to those of the components observed in the SN 1987A, and at velocities 310–320 km s^{-1}. If the gas showing up in Na I is the same as that producing the 21 cm emission, our optical absorption observations probe the distribution in depth of the sheets detected in radio surveys. In particular, the gas responsible for the 220 km s^{-1}, 250 km s^{-1}, and 269 km s^{-1} components, detected in 21 cm and toward the SN 1987A but not toward the two supergiants, should be located behind the main component at 270–280 km s^{-1}. The gas with velocities greater than 310 km s^{-1}, detected only in 21 cm, should be located even beyond the SN 1987A, in the rear regions of LMC.

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