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INTERSTELLAR MAGNESIUM ABSORPTION IN THE DIRECTION OF FOUR UNREDDENED STARS

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ABSTRACT

Spectral observations of the interstellar lines of Mg^+ at 2795 and 2802 Å and Mg^0 at 2852 Å have been made with a resolution of 0.1 Å, toward several stars, with an objective grating spectrograph mounted on a balloon-borne, star-stabilized platform. We discuss the analysis of the spectra of four, nearby, unreddened stars and derive values for the interstellar Mg abundance and electron density for the gas in these directions.

Subject headings: abundances — interstellar matter — spectra, ultraviolet

I. INTRODUCTION

In this *Letter* we report spectral observations of the interstellar lines of Mg^+ at 2795.53 Å and 2802.70 Å and Mg^0 at 2852.13 Å in the direction of four nearby unreddened stars. The spectra, covering the region 2870–2740 Å with a resolution better than 0.1 Å, were obtained from a balloon-borne instrument which has been described previously (Boksenberg *et al.* 1972, 1974, 1975). The instrument was launched on a 20×10^6 cubic foot (5.6×10^5 m^3) balloon from the National Scientific Ballooning Facility (NSBF) Balloon Flight Station, Palestine, Texas, at 19:17 CDST on 1974 May 19 and was cut down at 06:48 CDST on May 20, after the spectra of nine stars had been recorded. In the present communication we discuss the analysis of the spectra of four unreddened stars; the remaining results are the subject of a subsequent publication.

II. FLIGHT DATA

Relevant astronomical data pertaining to the four stars are given in Table 1. Spectral types, photometric data, distances and radial velocities were taken from Lesh (1968, 1972), with the exception of α Leo, for which we used the results of Iriarte *et al.* (1965). The intrinsic colors of Johnson (1963) were used in the determination of $E(B - V)$.

A microdensitometer tracing of the regions near to and including the Mg II and Mg I lines in σ Sgr is reproduced in Figure 1 as an example of the flight data. The individual equivalent widths measured for the Mg I and Mg II interstellar lines are listed in columns (2) and (3) of Table 2. The errors quoted reflect the uncertainties in placing the stellar continuum and the fog density, and include the extreme departures from the mean of the values determined from several tracings. The spectrum of η UMa shows an apparent absorption feature redshifted by 70 + 10 km s^{-1} from the expected position of the Mg I line, assuming that the neutral and singly ionized species are at rest with respect to each other. Additional observations of this star are needed in order to investigate further the reality of this feature, which, with an equivalent width of 10 ± 5 mÅ, is close to our detection limit.

III. MAGNESIUM COLUMN DENSITIES

Individual curves of growth, including radiation damping, were computed in order to derive the column densities of Mg^0 and Mg^+ for the interstellar medium in line to each star from the corresponding equivalent

TABLE 1

DATA FOR STARS OBSERVED*

HD No.	Star	Spectral Type	V	$E(B-V)$	Distance (pc)	l	b	v_r (km s^{-1})
87901........	α Leo	B7 V	1.35	0.00	22	226°	+49°	+ 4.0
120315........	η UMa	B3 V	1.84	0.02	41	101°	+65°	−10.8
175191........	σ Sgr	B3 IV	2.09	0.00	57	10°	−12°	−11.4
116658........	α Vir	B1 IV	0.97	0.03	86	316°	+50°	+ 0.8 (variable)

* See text for references.

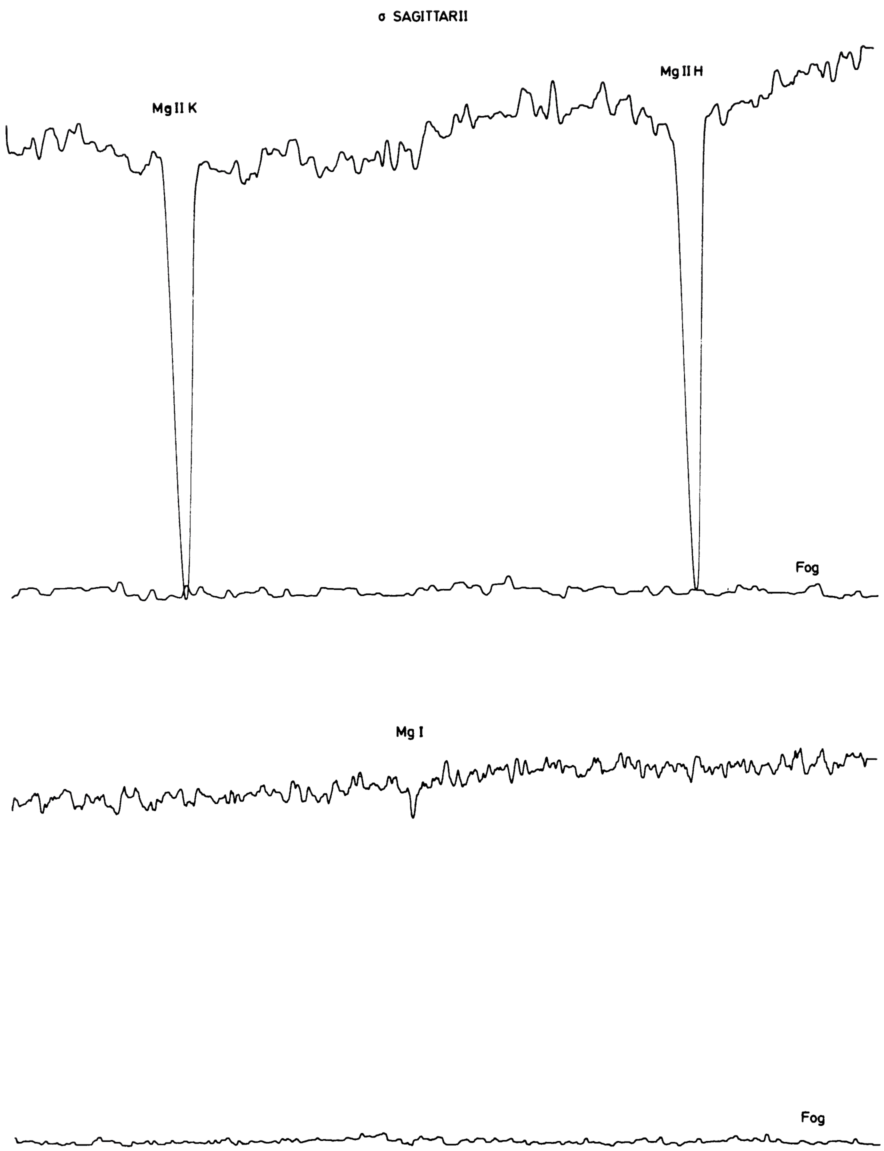

FIG. 1.—Sample microdensitometer tracings of the regions around the Mg II and Mg I lines in σ Sgr with comparison tracings of the film background.

TABLE 2

EQUIVALENT WIDTHS AND COLUMN DENSITIES

Star (1)	W(Mg^0) (mÅ) (2)	W (Mg$^+$) (mÅ) (3) h	k	b*(km s^{-1}) (4)	log N(Mg^0)† (5)	Log N(Mg$^+$)† (6)
α Leo.........	≤10	37±15	55±20	3 (+5, −1)	≤10.9	12.3 (+0.5, −0.3)
η UMa.......	≤10	46± 4	59± 5	2.5 (+0.5, −0.5)	≤10.9	12.6 (+0.2, −0.2)
σ Sgr.........	12±4	210±30	230±30	3.5–7.5	11.0 (+0.1, −0.2)	15.6–13.3‡
α Vir.........	30±5	157±20	169±20	2.5–5.5	11.5 (+0.1, −0.2)	15.4–13.3‡

* See text for definition of Doppler parameter b.

† N in cm^{-2}.

‡ Column densities strongly dependent on b value.

widths. The oscillator strengths were taken from Wiese *et al.* (1969). As no very high resolution spectral observations are available from which the velocity dispersion of the atoms in line to each star can be deduced (Hobbs, private communication), we have assumed that the velocity profile can be described by a single Gaussian. This assumption may indeed be valid for the low-density interstellar material under consideration here: the stars in Table 1 are close to the Sun ($d < 90$ pc) and are characterized by very low reddening [$E(B-V) \leq 0.03$].

The equivalent widths (or upper limits) of the Mg I lines were found to lie on the linear portion of the curve of growth, and hence yielded column densities which are essentially independent of the choice of the Doppler parameter $b(b = 2^{1/2}\sigma$, where σ is the rms velocity in line of sight for a Gaussian velocity distribution for the absorbing atoms). The Mg II h and k lines, on the other hand, are stronger and the corresponding column densities depend much more on the choice of b. However, b can be determined from the requirement that the derived column density of the gas in line to each star must conform with the observed Mg II H and K doublet ratio. Column (4) of Table 2 lists the derived b values, and columns (5) and (6) respectively give the corresponding column densities or upper limits for Mg^0 and and Mg^+. The uncertainties judged for each result on the basis of the systematic errors in equivalent width are also indicated. We briefly discuss each star individually:

α Leonis.—In the case of this star a single Gaussian velocity distribution defined by $b = 3$ km s^{-1} reproduces the observed doublet ratio exactly, but any Gaussian with $2 < b < 8$ km s^{-1} is also consistent with the data. The resulting Mg^+ column density, however, is rather insensitive to the choice of b value, since the doublet ratio is greater than $\sqrt{2}$ and the h and k lines lie on the linear portion of the curve of growth. Rogerson *et al.* (1973) reported $\log N(Mg^+) = 12.47$, from a *Copernicus* observation of one line of the Mg II doublet toward this star, assuming $b = 10$ km s^{-1}. These parameters yield equivalent widths of the h and k lines which are more than 60 percent greater than our values.

η Ursae Majoris.—The doublet ratio measured toward this star implies $b = 2.5$ km s^{-1} and $\log N(Mg^+) = 12.6$. This is twice the value derived in the direction of α Leo, which is at half the distance. Consequently, we find the same average space density [$\bar{n}(Mg) = 3.3 \times 10^{-8}$ atoms cm^{-3}) toward these two nearby, high galactic latitude stars, assuming magnesium to exist predominantly as Mg^+ and to be evenly distributed along the lines of sight. The low b value obtained for η UMa gives additional support to the assumption that the gas in this direction is not concentrated in a multiple cloud system, since the latter probably would yield a larger value of b as a result of blending between different components.

α Virginis and σ Sagittarii.—The Mg II lines detected in the lines of sight to these two stars lie on the flat part of the curve of growth (doublet ratio ~ 1.1), where the equivalent widths are not very sensitive to large changes in the column density. Consequently, the latter quantity is rather poorly determined and for both stars we find an uncertainty of approximately two orders of magnitude in the derived value of $N(Mg^+)$. Conversely, the weaker Mg I absorption lines give an accurate estimate of $N(Mg^0)$, irrespective of the adopted b value.

IV. MAGNESIUM INTERSTELLAR ABUNDANCES

The determination of the relative abundance of magnesium to hydrogen in the low density interstellar medium is made somewhat uncertain by the lack of accurate data on N(H) in the directions of most of the stars listed in Table 1. Bohlin (1975) reported $N(\mathrm{H\,I}) < 1 \times 10^{19}$ and $<3 \times 10^{19}$ atoms cm^{-2} toward α Vir and σ Sgr, respectively, from *Copernicus* observations of interstellar absorption at Lα. The later spectral types of α Leo and η UMa (B7 and B3, respectively) and their close proximity entail that the stellar Lα line strongly dominates the interstellar component, thus rendering a reliable measurement of the latter very difficult.

In the following discussion we assume magnesium to be present in the low density interstellar medium predominantly in the form of Mg^+, the lowest ionization stage whose ionization potential exceeds that of hydrogen, and accordingly we adopt the reported Mg^+ column densities as representative of the total amount of magnesium in line to each star. As a check on the validity of this assumption, we carried out some simple calculations aimed at assessing the contribution of the individual stellar fluxes and of a diffuse Lyman continuum to the general stellar photon radiation field (see also Torres-Peimbert *et al.* 1974). We found that the amount of Mg^{++} expected in the direction of the four stars observed is not likely to be significant for the purpose of estimating magnesium to hydrogen abundances.

The Mg^+ column densities measured toward α Leo and η UMa are the lowest observed in our program, both stars yielding $\bar{n}(Mg) = 3.3 \times 10^{-8}$ atoms cm^{-3}. If Mg exists in these thin regions with solar abundance (3.5×10^{-5} [Withbroe 1971]), it would imply $\bar{n}(H) < 1 \times 10^{-3}$ atoms cm^{-3}. Although this is a very low value, it is interesting to note that Bohlin (1975) derived $\bar{n}(H) < 1 \times 10^{-2}$ cm^{-3} toward β and ε CMa, at a distance of approximately 200 pc. On the other hand, several authors have reported $\bar{n}(H) = 1$–2×10^{-1} atoms cm^{-3} within 140 pc of the Sun (see Bertaux *et al.* 1972; Rogerson and York 1973; Savage and Panek 1974; Jenkins and Savage 1974). If the density of the gas in the directions of α Leo and η UMa were of this order, our results would imply a depletion of magnesium by a factor 100 with respect to the solar ratio.

The stronger Mg II lines observed in the directions of α Vir and σ Sgr indicate the presence of material of higher density than is observed toward α Leo and η UMa. However, the poor determination of the Mg^+ column density resulting from the uncertainty in the value of b makes conclusions concerning the Mg/H abundance rather tentative. Using the *Copernicus* upper limits of N(H) toward these two stars, we are able to set lower limits to the Mg/H abundance. For α Vir the lower limit on b of 2.5 km s^{-1} indicates an overabundance by at least a factor 7 while the upper limit $b = 5.5$ km s^{-1} implies an underabundance by a factor 18 at most. For σ Sgr, the corresponding lower limits to Mg/H abundance lie between 4 and 0.02 times the solar value.

Data pertaining to the above discussion are given in Table 3. As a final comment in this context it may be said that a normal Mg/H abundance is not ruled out by any of the present results.

V. ELECTRON DENSITY

Assuming that the process of ionization is due to the general stellar radiation field and that recombination occurs by collision between ions and free electrons, the relative numbers of singly ionized and neutral Mg atoms are given by

$$\frac{n(\mathrm{Mg}^+)}{(\mathrm{Mg}^0)} = \frac{\Gamma(\mathrm{Mg}^0)}{\alpha_{\mathrm{TOT}}(\mathrm{Mg}^0)n(e)} .$$

In the derivation of the photoionization rate $\Gamma(\mathrm{Mg}^0)$ we have used the data of Witt and Johnson (1973) for $u(\lambda)$ (the interstellar radiation density) and of Dubau and Wells (1974) for $a(\lambda)$ (the photoionization cross section of Mg^0). The resulting value of Γ is 8×10^{-11} s^{-1}. More recent calculations of the interstellar radiation flux by Gondhalekar and Wilson (1975) yield a value for $\Gamma(\mathrm{Mg}^0)$ about a factor 2.5 lower than used here. The recombination coefficient $\alpha_{\mathrm{TOT}}(\mathrm{Mg}^0)$ is the sum of radiative and dielectronic coefficients obtained respectively from Peach (1967, 1974) and Burgess (1965). At 10^4 K, generally considered to be representative of the temperature of the low density intercloud medium, $\alpha_{\mathrm{TOT}}(\mathrm{Mg}^0) = 1.0 \times 10^{-11}$ cm^3 s^{-1}. This is also the value at a gas temperature of 60–70 K, which we assume to be typical of interstellar clouds. A more detailed discussion on the parameters $u(\lambda)$, $a(\lambda)$, and $\alpha(\mathrm{Mg}^0)$ can be found in a previous publication (Boksenberg *et al.* 1975). For the ratio $n(\mathrm{Mg}^+)/n(\mathrm{Mg}^0)$ we take $N(\mathrm{Mg}^+)/N(\mathrm{Mg}^0)$, the ratio of column densities, with the implicit assumption that the space distributions of Mg^+ and Mg^0 largely correspond. The values of electron density $n(e)$ thus derived are listed in Table 3.

α Leonis and η Ursae Majoris.—The small distance and low reddening of α Leo support the picture of a uniformly distributed, low-density interstellar medium for which the above assumption appears justified. As the Mg I line in this direction is below our limit of detection, we can only place an upper limit on $n(e)$: ≤ 0.6 cm^{-3}, assuming $T = 10^4$ K. The upper limit would be further increased if $T < 10^4$ K. In the case of η UMa, if the feature near the position of the Mg I line mentioned in § II is not real, similar arguments could apply and we should derive $n(e) \leq 0.3$ cm^{-3}. On the other hand, if the feature is real, it may indicate the existence of a high-density condensation within the H II region of the star.

α Virginis and σ Sagittarii.—York (1974*a*) reported the detection of interstellar O VI lines in the direction of α Vir, indicating the presence of a very hot ($\log T = 5.3$–5.6), very low density [$n(\mathrm{H})_{\min} \approx 10^{-3}$ cm^{-3}] plasma, thought to contain approximately 1 percent of the total amount of gas and to occupy between 20 and 100 percent of the line of sight. However, the Mg II and Mg I lines discussed here are not formed in this phase of the interstellar medium ($\log T \geq 5.3$ implies $b \geq 11.6$ km s^{-1} for Mg ions; moreover, from the calculations of Jordan 1969 it is evident that at such high temperatures all Mg has been converted to higher ionization stages than Mg^+) but rather in an H I or possibly H II region which may be embedded in the hot interstellar plasma. A comparison of the spectrum of α Vir with the laboratory reference spectrum showed no measurable velocity shift between the Mg II doublet and the Mg I line, thus lending support to the assumption that $N(\mathrm{Mg}^+)/N(\mathrm{Mg}^0) \approx n(\mathrm{Mg}^+)/n(\mathrm{Mg}^0)$ may be a reasonable approximation to the true physical situation (see York 1975). The lower limit on $n(e)$ could point to the existence of a cold ($T \approx 60$ K), low-density, H I region similar to those observed in the directions of the Orion stars (Boksenberg *et al.* 1972, 1974, 1975; Bates *et al.* 1975), where we deduced photoionization by starlight to be the predominant electron-producing process. Thus, combining the ratio $n(e)/n(\mathrm{H}) \approx 5 \times 10^{-4}$, which assumes normal elemental abundances, and $n(e) \geq 1 \times 10^{-3}$ cm^{-3}, we derive a minimum value of $n(\mathrm{H})$ in the H I region of approximately 2 atoms cm^{-3}. Comparing

TABLE 3

ABUNDANCES AND ELECTRON DENSITIES

Star	b (km s^{-1})	$\log N(\mathrm{H})$*	$N(\mathrm{Mg})/N(\mathrm{H})$	$n(e)$ (cm^{-3})
α Leo.......	3 (+5, −1)	16.8 (+0.5, −0.3)†	3.5×10^{-5}‡	≤ 0.6
η UMa.....	2.5 (+0.5, −0.5)	17.0 (+0.2, −0.2)†	3.5×10^{-5}‡	≤ 0.3
σ Sgr.......	3.5–7.5	<19.5§	1.3×10^{-4}–6.7×10^{-7}‖	2×10^{-4}–4×10^{-2}
α Vir.......	2.5–5.5	<19.0§	2.5×10^{-4}–2.0×10^{-6}‖	1×10^{-3}–1×10^{-1}

* N in cm^2.

† Derived from measured $N(\mathrm{Mg}^+)$ assuming solar abundance.

‡ Solar abundance, Withbroe 1971.

§ Bohlin 1975.

‖ Lower limit values.

this estimate with the mean $\bar{n}(\mathrm{H}) \leq 0.04\ \mathrm{cm}^{-3}$ derived from *Copernicus* observations of Lα absorption, we conclude that this region would occupy at most 2 percent of the line of sight to α Vir.

On the other hand, the upper limits of b and $n(e)$ could entail a partial ionization of hydrogen, thus suggesting a low-density, high-temperature ($T \approx 10^4$ K), "intercloud medium," ionized by α Vir and the flux of Lyman continuum photons provided by O and early B stars not associated with normal H II regions (see Mészáros 1974 and Torres-Peimbert *et al.* 1974). The proportion of hydrogen present as H^+ would depend on the size of the region embedded in the hot plasma. We feel that this interpretation is more plausible than the former, in view of the fact that the case $b = 2.5\ \mathrm{km\ s}^{-1}$ yields a relative abundance of Mg at least an order of magnitude greater than the solar value. The derived upper limit $n(e) \leq 10^{-1}\ \mathrm{cm}^{-3}$ is compatible with the mean value $n(e) \leq 4 \times 10^{-2}\ \mathrm{cm}^{-3}$ deduced by York (1974*b*) in the direction of α Vir, from a study of the population of the excited fine-structure levels of C II, Si II, and N II.

A similar situation is encountered in the case of σ Sgr, in which direction we deduce $2 \times 10^{-4} \leq n(e) \leq 4 \times 10^{-2}\ \mathrm{cm}^{-3}$ for $3.5 \leq b \leq 7.5\ \mathrm{km\ s}^{-1}$, assuming that the spatial distributions of Mg^+ and Mg^0 largely correspond. However, a measurement of the Doppler shift between the Mg I line and the Mg II doublet yielded the value $-10 \pm 10\ \mathrm{km\ s}^{-1}$, although further observations are required to verify this. If this difference in relative velocity is real, it could indicate the existence of a circumstellar H II region, possibly containing a fraction of the observed Mg^+ and most of the Mg^0.

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