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THE INTERSTELLAR LINES OF THE FEIGE STARS

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ABSTRACT

New measurements of the equivalent widths and radial velocities of the interstellar lines of Ca II and Na I in the spectra of Feige stars are presented. The upper limits to the Na I interstellar line imply that the gas in the halo has a much larger value of the ratio of the column density of Ca II to that of Na I than does the plane, and that this ratio is larger than the intermediate value obtained previously from a group of brighter halo stars. From this we deduce that there is gas up to at least 1 kpc above the plane, and that this gas has much more Ca II relative to Na I than does the plane. The interstellar equivalent width corresponding to looking out of the Galaxy from the plane at $b^{II} = 90°$ is about 300 mÅ for the stronger of the Ca II lines. The velocity measurements imply that this gas is moving slowly toward the plane in a time scale such that replenishment of the halo gas is necessary.

Subject headings: abundances — faint blue stars — galactic structure — interstellar matter

I. INTRODUCTION

A survey of faint blue stars near the galactic poles was compiled by Feige (1958). This list provides a useful probe for investigating the interstellar medium (IM) far above the plane. The principal problem of the Feige stars is that their luminosities are not known accurately. Some of the stars are subluminous or field horizontal-branch stars, and at the low dispersions available the luminosity of the stars and hence the heights above the plane (Z) are uncertain. Previous studies by Greenstein (1968) and Sargent and Searle (1968) have focused on the spectra of the stars themselves and of the interstellar K-line of Ca II. New observations of the interstellar Ca II and Na I lines in the Feige stars are presented in § II. The interpretation of these observations in terms of the peculiar relative abundances of Ca II, Na I, and H I, and also of the peculiar velocity distribution of the observed components, is discussed in § III. We find the Feige stars to be even more extreme, as compared with stars in the plane, than the brighter halo stars of Cohen (1974) in the peculiarities of the interstellar lines. We conclude from two separate lines of evidence that there must be gas containing Ca II at $Z = 1$ kpc, with a ratio of Ca II/Na I much larger than in the plane, and an enhancement of Ca II relative to H I. In § IV we discuss a model where the halo gas is falling toward the plane and is continually being replenished, which model is forced upon us by the radial velocity data. We also speculate briefly on the relationship between the optical gas and the high-velocity radio gas.

II. OBSERVATIONS

A catalog of faint ($9.5 < M_V < 13.0$) underluminous hot stars at high galactic latitudes was compiled by Feige (1958). Many of them are O and B stars which show interstellar lines. High-dispersion spectra of several of these objects taken at the Lick Observatory by R. Kraft, K. Anderson, W. L. W. Sargent, and L. Searle were generously loaned for this investigation. In addition, the plate files of the Hale Observatories were searched for additional spectra.

Thirty spectra of O- and B-type stars were taken in the blue on 103a-O plates at Lick Observatory during the years 1965–1969 with a wavelength range between 3600 and 4600 Å and a dispersion of 47 Å mm^{-1}. Twenty-two of these were among the spectra used by Sargent and Searle (1968). Nine more were taken in the blue at Palomar Mountain in 1966–1967 using baked IIa-O plates. Their range was 3400–4800 Å with a dispersion of 10 Å mm^{-1}. Using 39 plates, representing 23 different stars, we measured equivalent widths and radial velocities from the Ca II K-line at 3933 Å. Although all but eight of the 39 blue spectra had been previously measured by Sargent and Searle (1968) or Greenstein (1968), we felt it necessary for reasons of uniformity with other papers in this series to measure all the spectra ourselves. A comparison of our measurements with those previously published is given in columns (2) and (3) of Table 2.

In addition, seven spectra were taken at the Lick Observatory in 1970 on 103a-D plates using a Varo image intensifier (Zappala 1971) with a central wavelength of 6100 Å and a dispersion of 35 Å mm^{-1}. These provided upper limits on Na I abundances.

The 23 stars which were chosen for study are listed in Table 1. Their color excesses were calculated using observed $B-V$ given by Sargent and Searle (1968) and the calibrations of Schild, Peterson, and Oke (1971). Distances above the galactic plane were determined using absolute magnitudes from Allen (1963) and the apparent magnitudes listed by Sargent and Searle (1968), assuming that the stars are either main-sequence or horizontal-branch types. Distances are given in Table 1 only for stars with relatively normal spectra, so that more or less reliable values of Z could be calculated.

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TABLE 1

Basic parameters of observed Feige stars

No.	Spectral Type	E_{B-V}	V_{LSR}	V^i_{LSR}	No. of Blue Spectra	Z
F10	Ao		- 19	-16[1]	1	
F11	Bp	0.0	- 46:	- 6	2	
F16	Ao		+ 9	+12[1]	1	
F23	B8, B6	0.0	- 27	-15	1	1500
F25	B7, B6	0.09	+ 36	+ 7	1	2700
F29	B4	0.06	- 12	- 9	3	1800
F34	Bp, sdO	0.0	+ 61:		1	
F36	sdB	0.0	+ 27	-29:	1	
F40	B4, B5	0.03	+ 79	- 5	2	2900
F51	B6, B8	0.0	+ 41	-18	2	1400
F56	B8, B6	0.01	+ 43	- 4	4	
F65	B2, sdB	0.0	+ 70	+67[1]	2	
F66	O, sdB	0.0	+ 6	+ 1	1	
F70	B8, Bw	0.01	+ 26	-30[1]	1	
F71	B9, B8III	0.0	+ 3	-11[1]	1	1100
F80	Op, sdO+A		+ 53	+49[1]	1	
F84	B3, sdB_3	0.04	+179	+31	1	
F86	B6, B5, Bw	0.0	- 12	- 8	4	
F92	Bpk, Bw, B7	0.02	+ 19	+ 8	4	
F99	B5, Bpk	0.01			0	
F101	Ao, Bw	0.0	+ 56	+53[1]	1	
F110	Bp, sdO	0.0	+ 33		1	
F111	B8, Bw	0.11	- 31	- 1[1]	1	

[1]λ3933 Å probably or certainly stellar.

Radial velocities were measured for the stars and for the interstellar Ca II K-line using the oscilloscope Grant machine of Kitt Peak National Observatory (KPNO) and are listed, relative to the local standard of rest, in Table 1. The stellar radial velocities are based on the lines Hγ, Hδ, H8 to H11, plus the strong He I lines when visible. In several cases where the lines are broad, the stellar V_r are quite uncertain. Although there is only one interstellar line (λ3933), it is sharp, and therefore we expect the V_r^i velocities to be as accurate as V_r. The general accuracy is shown by the good agreement between the two measurements for F10 and F16, which are A0 stars, and by the good agreement with the measurements of Berger (1963) for the nine cases in common. We expect that in cases where there is only one spectrogram available, V_r^i should be accurate to ± 15 km s^{-1}.

The PDS digital microphotometer at KPNO was used to scan the spectra. Calibration exposures taken on either side of the stellar spectra allowed the conversion of density into intensity. Equivalent widths (Table 2) were measured for the Ca II K-line and Na I D-lines. The width of the K-lines, combined with the radial velocity data, provided a good discriminant between stellar and interstellar K-lines in suspicious cases. The full widths at half-maximum for Ca II were typically on the order of 1–2 Å, and the interstellar lines were barely resolved. The Ca II H-line is too blended with Hε at such a low dispersion to be measured.

TABLE 2

W_λ for interstellar lines in the Feige stars

Star	W_λ 3933	W_λ 3933*	W_λ 5889	W_λ 5895
F11	110			
F23	300:	250		
F25	260	370		
F29	295	370	320	300
F34	≤ 70			
F36	≤ 75			
F40	305	350	≤110	
F51	240	185	≤110	
F56	340	280	≤110	
F66	200:	170		
F84	290:	370		
F86	135	115	≤110	
F92	255	260	≤110	
F99		155	≤110	
F110	≤100			

*mean of Sargent and Searle (1968) and Greenstein (1968)

III. DISCUSSION

The pattern of W_λ given in Table 2 for the interstellar lines in the Feige stars is rather different from that observed in the plane (see, for example, Cohen 1975). Normally, in the plane, the stronger Ca II line is slightly weaker than the stronger line of the yellow Na I doublet, except in a few cases with high radial velocities in the LSR system. Here there are seven measurements or limits for the ratio $\mathscr{W} = W_\lambda$ (Ca II λ3933)/W_λ (Na I λ5889). In only one case is $\mathscr{W}$ less than 1. In four of the six cases with upper limits for W_λ of the Na I line, $\mathscr{W}$ is greater than 2. In the other two cases, the Ca II line is only slightly stronger than the Na I upper limit, so that all we can say is $\mathscr{W} > 1$. If we assume that the doublet ratios are the same for the Ca II and Na I doublets, then $\mathscr{W} > 2$ implies that N(Ca II)/N(Na I) > 4. Any reasonable

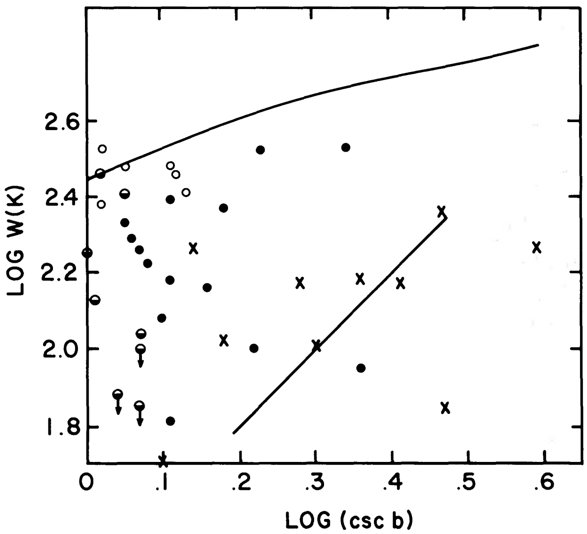

FIG. 1.—A plot of the equivalent width of the interstellar K-line of Ca II as a function of csc(b^{II}). *Open circles*, Feige stars not classified as subdwarfs or peculiar spectroscopically. *Half-filled circles*, Feige stars which are probably subluminous. *Filled circles*, the brighter halo stars (group B) which have $Z > 500$ pc, while the ×'s are the halo stars with $Z < 500$ pc. The lower solid line represents the theoretical prediction for unsaturated lines (eq. [1]), while the upper solid line is the predicted curve for saturated lines.

allowance for the different curve-of-growth effects expected for the D-lines, with $W_\lambda \leq 100$ mÅ as compared to $W_\lambda = 200$ to 300 mÅ for the stronger Ca II line, implies that for $\mathscr{W} > 2$, $N(\text{Ca II})/N(\text{Na I}) > 8$. We therefore argue that the one case with $\mathscr{W} < 1$ is that of a cloud very close to the plane on the line of sight to a distant halo star. The material actually far above the plane has $\mathscr{W} > 2$; hence, $N(\text{Ca II})/N(\text{Na I}) > 8$. If we compare this with the summary given in Table 6 of Cohen (1975), we see that the Feige stars represent a more extreme case of the characteristics ascribed to the brighter halo stars by Cohen (1974). This is not unreasonable, since we expect the Feige stars, with fainter apparent magnitudes than those given for the brighter halo stars by Cohen (1974), to have, on the average, higher values of Z. This strengthening of the halo pattern of interstellar lines (i.e., strong Ca II relative to Na I) in the Feige stars implies that there is actually material high in the halo between the mean Z of the Feige stars and that of the brighter stars of Cohen (1974)—i.e., material at least up to $Z = 1$ kpc.

Is there any other evidence that there is actually material containing Ca II that high in the halo? In Figure 1 we plot the logarithm of $W_\lambda(K)$ versus the logarithm of csc(b^{II}). The Feige stars are divided into those which appear to have normal spectra (*open circles*) and those which are classified by either Greenstein (1968) or Sargent and Searle (1968) as subdwarfs. We expect the latter group to be subluminous and hence closer to the plane. The dots indicate the stars of Cohen (1974) and Münch and Zirin (1961) with $Z > 500$ pc, which are in the mean not as high as the fainter Feige stars. (We shall refer to these brighter halo stars as group B.) The ×'s indicate the stars of Cohen (1974) with $Z < 500$ pc, but $b^{II} > 15°$. If the interstellar medium above the plane is idealized as consisting of plane-parallel layers, then for unsaturated lines,

$$W_\lambda(K) = W^0 f(Z/Z_{\text{top}}) \csc(b^{II}) . \qquad (1)$$

Here W^0 is the W_λ resulting from looking at $b^{II} = 90°$ at a value of Z above the layer of gas whose upper limit in height above the plane is Z_{top}. For layers of uniform density, $f(Z/Z_{\text{top}}) = Z/Z_{\text{top}}$, while in all cases $f(Z/Z_{\text{top}})$ increases monotonically to 1 at $Z = Z_{\text{top}}$. The straight line on Figure 1 represents equation (1) in the regime of its validity, where $W_\lambda(K)$ is small. The curved line is an attempt to correct equation (1) for saturation in the case of large values of $W_\lambda(K)$.

Not surprisingly, the observations displayed in Figure 1 show the expected behavior. W^0 appears to be about 300 mÅ as judged by the Feige stars with normal spectra. (Greenstein [1968] obtained $W^0 = 400$ mÅ from his version of Figure 1 with the data then available.) Those Feige stars which from spectroscopic evidence seem to be subluminous indeed fall toward the lower part of the figure, implying a lower value of Z. The stars of group B appear to have heights intermediate between those of the subdwarf Feige and normal Feige stars. Most important, the value of $W_\lambda(K)$ at b^{II} close to 0 keeps increasing as the mean expected value of Z increases; i.e., the normal Feige stars have values of $W_\lambda(K)$ larger than those of group B stars at similar galactic latitudes. This is conclusive evidence for gas at heights of at least 1 kpc.

Now let us consider the question of whether the halo gas has an excess of Ca II relative to H I, or a deficit of Na I. Although the values of E_{B-V} are uncertain, a maximum value is 0.10 mag, implying a maximum value of log $N(\text{H I}) = 20.8$ cm^{-2}, using the ratio $E_{B-V}/N(\text{H I})$ given by Jenkins and Savage (1974). In Cohen (1974) we demonstrated that the ratio $E_{B-V}/N(\text{H I})$ is not smaller at high galactic latitudes than it is in the plane. From the values of W_λ for the cases with $\mathscr{W} > 2$, we obtain a minimum of log $N(\text{Ca II}) = 12.8$ cm^{-2} (since we do not know the doublet ratio), and a maximum value of log $N(\text{Na I}) = 11.8$ cm^{-2} (since we have only an upper limit on W_λ). The resulting ratios of minimum log $[N(\text{Ca II}/\text{H I})] = -8.0$ indicate clearly, when compared with Table 6 of Cohen (1975), that there is a strong excess of Ca II relative to H I as compared with the plane. This again is an amplification of the behavior of the brighter halo stars discussed by Cohen (1974). Of course, it may be that most of the H I is in the plane, and the hydrogen above the plane, if present, is ionized, whereas most of the Ca II cannot be in the plane.

Let us now consider the measured radial velocities in the LSR system. First, the normal B stars located at $Z > 500$ pc must be runaway B stars, and should have large stellar radial velocities. This is certainly the case for F40, F51, and F56, which strengthens the evidence from their spectral types that these stars are far above the plane.

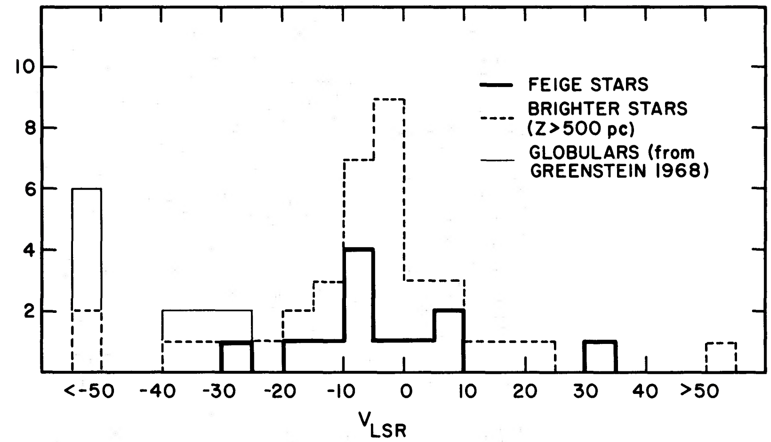

FIG. 2.—A histogram of the velocities in the LSR system of the components of the interstellar lines observed in various groups of halo stars. The heavy solid line refers to the Feige star velocities; the dotted line, to the stars of group B (the brighter halo stars); the thin solid line, to the globular cluster stars.

We also note that the agreement between the predicted V_{LSR} from galactic rotation,

$$V_{LSR}^{pred} = Ar \sin (2l^{II}) \cos^2 b^{II} ,$$

and the observed V_{LSR} is terrible, and in most cases no value of r can be deduced which is less than the distance of the star. Although the errors in the measurement of V_r are large as a result of the low-dispersion spectra, stronger evidence for the lack of corotation with the plane for gas at high galactic latitudes has been discussed, using more accurate radial velocities by Cohen (1974).

In Figure 2 we plot a histogram of V_{LSR} for each interstellar component for several groups of stars: the Feige stars from the data of Table 1, the brighter halo stars of group B, and the measurements of Greenstein (1968) for globular cluster stars. In the last group, there may be some problem of contamination by faint background stars in the cluster, and hence these velocities are the least reliable. The distribution appears skewed toward negative values of V_{LSR}. This impression is confirmed by the averages given in Table 3. The last entry was an attempt to remove the effect of the local components arising within the plane ($Z < 100$ pc), which will have V_{LSR} close to 0. We note that *all* the averages are negative, suggesting that the gas in the halo that is seen in the Ca II interstellar line on the average is falling toward the plane at a radial velocity (V_{LSR}) of about -6 km s^{-1}. This is much smaller than the velocities of about -100 km s^{-1} (Dieter 1971) ascribed to the high-velocity clouds of neutral hydrogen falling toward the disk.

TABLE 3

AVERAGE VALUE OF V_{LSR}

Parameter	Feige Stars	Group B	Feige + Group B $\lvert V \rvert \geq 5$ km s^{-1}
V_{LSR}..........	-4	-6	-7.5
Number of components...	12	26	30

The interpretation of the halo gas, derived from the optical interstellar lines, as slowly moving toward the plane, is similar in some respects to that of the very early radio studies as analyzed by Helfer (1962) and Blaauw (1962). It is not clear whether the negative velocities are confined largely to the region l^{II} from 100° to 180° as suggested by Blaauw. Most of Heiles gas ($-20 \leq V_{LSR} \leq -92$ km s^{-1}) is in that region. Furthermore, the most extreme negative velocity interstellar components in stars are at galactic longitude 84° and 183°, with almost no components observed at longitudes between 85° and 180°. If all the interstellar components in the three stars near $l^{II} = 84°$ and 184° with the largest negative velocities are removed from the sample, the average LSR velocity of the interstellar components in the remaining halo stars (excluding globular cluster stars) becomes almost 0. Thus it is not clear whether the predominance of negative radial velocities is global or is confined to a range in galactic longitude from about 80° to 185°.

The most peculiar V_{LSR} in Figure 1 is that of a component of HD 203664 at $+76$ km s^{-1}. This star is not in the direction of the region of the Magellanic stream with large positive radial velocities (Mathewson, Cleary, and Murray 1974), and therefore the origin of this component is puzzling.

IV. CONCLUSIONS

From the interstellar lines observed in the Feige stars, we have found that there must be gas at least 1 kpc above the plane. This gas has a ratio of N(Ca II)/N(Na I) at least 8 times larger than that observed for the plane. Furthermore, the N(Ca II)/N(H I) ratio is larger than that in the plane. We have also noted that the distribution of radial velocities in the LSR system is skewed negative. This holds at both positive and negative values of galactic latitude. We thus can imagine a model where the halo gas is, on the average, falling toward the plane with a mean V_{LSR} of 5 km s^{-1}. Material 1 kpc above the plane will require no more than 2×10^8 years to reach the plane, and the fall time could be shorter due to gravitational acceleration near the plane. This implies that the halo is being emptied of gas either globally or in a certain range of galactic longitude, and hence must be replenished either by gas ejected from the plane (perhaps from supernova explosions), by mass loss from stars in the halo, or by intergalactic gas falling in (Oort 1970). The mass of the halo gas inferred from the observed interstellar lines is 1–6 $\times 10^7 M_\odot$ (Cohen 1975). If the mass loss from halo to plane is global, this mass loss is larger than any reasonable estimate of the mass ejection expected in the course of stellar evolution for stars in globular clusters, which is of the order of $10^5 M_\odot$ of gas in 10^8 years (Knapp, Rose, and Kerr 1974). The extremely uncertain estimate of mass loss by Mira variables with $Z > 1$ kpc in the halo is $10^{-1} M_\odot$ per year (Gehrz and Woolf 1971). This may be sufficient to account for the gas seen optically, although it would be hard to explain the presence of clouds with positive radial velocities. If this is the source of most of the halo gas, one might expect interstellar grains in the halo.

The relationship between the radio high-velocity gas and the gas seen optically remains very unclear. Observations of interstellar lines in spectra of external galaxies and globular cluster stars as well as a search for halo stars with l^{II} between 90° and 180° would help a great deal in elucidating the location and motion of the gas.

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