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INTERSTELLAR MOLECULAR LINES IN *A* STARS

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ABSTRACT

Seven A and two B9 stars near the galactic plane were observed spectroscopically in the blue region. Two of these stars and possibly a third one show interstellar lines of CN. From the CN lines of HR 618 an excitation temperature $T_E = 3.7 \pm 0.7$ °K was derived and from HR 1035 a T_E smaller than 4 °K was obtained. From the stellar radial velocity, the spectroscopic parallax, and the velocity profile of the interestellar Ca II lines it is argued that HR 618 is located in the Perseus arm while the CN lines projected on the star originate in the Orion arm, in a region free of ionized hydrogen; these results are in agreement with the "3 °K" blackbody radiation field. Interstellar lines of CH^+ were also detected in five of these objects. It is shown that al least in two cases the CH^+ lines are not circumstellar.

SUMARIO

Se observaron espectroscópicamente en el azul siete estrellas A y dos estrellas B9, situadas cerca del plano galáctico. Dos de ellas y posiblemente una tercera muestran líneas interestelares de CN. A partir de las líneas de CN en HR 618 se encontró una temperatura de excitación $T_E = 3.7 \pm 0.7$ °K, y en HR 1035 se obtuvo una T_E menor que 4 °K. La velocidad radial de esta estrella, su paralaje espectroscópico y el perfil de las líneas interestelares de calcio indican que HR 618 se encuentra en el brazo de Perseo, mientras que las líneas de CN proyectadas en la estrella se originan en el brazo de Orión, en una región exenta de hidrógeno ionizado. Estos resultados concuerdan con el campo de radiación Planckiano de 3 °K. También se detectaron líneas interestelares de CH^+ en cinco de estas estrellas. Se muestra que cuando menos en dos casos las líneas de CH^+ no son circunestelares.

I. Introduction

There have been several investigations on the behavior of interstellar lines. The classic work by Adams (1949) with the 100-inch telescope at Mount Wilson comprised 300 stars, mainly of types O and B, south of $\delta = 50°$. Münch (1953, 1957) noticed that only 10% of these stars were farther away than 1 kpc; with the aid of the 200-inch telescope he investigated further the interstellar lines to regions north of $\delta = 50°$, including thus a large fraction of stars farther away than 1 kpc. From his investigations he confirmed the existence of the spiral arm structure of our galaxy first delineated from O and B associations by Morgan, Sharpless, and Osterbrock (1952).

Several investigators have suggested that if the universe really originated in a "big bang", radiation remaining from the explosion should still be present. Gamow (1948, 1956), predicted $T \approx 6$ °K for the present stage of the universe. This idea was reviewed by Dicke, Peebles, Roll, and Wilkinson (1965) who predicted a Planckian background radiation with a temperature of 1 to 10 °K. Pensias and Wilson (1965) were the first to measure the background radiation field and found $T = 3.5 \pm 1$ °K from $\lambda 7.4$ cm observations. Since then, other observers have made several measurements at different wavelengths in the radio region, finding $T \approx 3$ °K.

Field and Hitchcock (1966) determined the excitation temperature of interstellar CN molecules from the spectra of ζ Oph as being $T_E = 3.22 \pm 0.15$ °K and of ζ Per as $T_E = 3.00 \pm 0.6$ °K. After examining various possible sources of excitation they reached the conclusion that a new source of 2.6 mm radiation was needed and linked this source with the background radiation found at $\lambda 7.4$ cm. They also showed that the radiation cannot be due to a dilute black-body originating at higher temperatures.

Münch (1964) suggested that in the case of the emission nebula Sh171 (Sharpless 1959) the CN molecules projected on a group of stars might be formed from interstellar grains exposed to the ultraviolet radiation of an advancing ionization front. In such case, it would mean that part of the CN excitation might indeed be due to collisions (Thaddeus and Clauser 1966). However, Clauser and Thaddeus (1967) and Thaddeus (1968) have studied 10 stars in which the CN excitation temperature is very much alike; this situation would have required the existence of the same proton density in the H II regions, which is very unlikely.

Bates and Spitzer (1951) suggested that the molecular lines, mainly those of CH^+, could be interstellar or circumstellar. They found in Adams's, list that in stars of low reddening ($E \leqslant 0.05$) the molecular residual velocity was positive which was taken as an indication that the lines were produced by circumstellar clouds. The particular mechanism proposed to produce the CH^+ molecules was the sublimation of CH_4 from grains near the stars. Rogerson, Spitzer, and Bahng (1959) measured the equivalent widths of $\lambda 4232$ (CH^+) in nine stars, five with low obscuration, and found that the latter equivalent widths were close to the theoretical prediction of Bates and Spitzer; i.e., the later the spectral type, the stronger the CH^+ line.

The study of interstellar molecular lines in A stars has been considerably neglected due to the circumstance that A stars show strong stellar lines of Ca II which very often appear blended with the interstellar lines. For example, in the study of Adams (1949) only 2 out of the 300 stars investigated were A stars; of the 112 stars observed by Münch (1957) only 10 were A stars and out of these 10 only one was observed in the blue region —the region of the molecular lines—; the 10 stars studied by Thaddeus and Clauser are stars of spectral type B5 or earlier and therefore associated with H II regions; an additional star observed by Herbig, which also shows an excitation temperature of 3° K (HR 1297, Thaddeus, private communication), is B8 II-III.

Since our knowledge of interstellar molecular lines in A stars is very scanty we decided to study a group of distant A stars. The advantages of studying A stars are the following: first, A stars are not generally associated with H II regions, thereby ruling out that part of the CN excitation might be due to proton collisions; second, if the theory of Bates and Spitzer is correct, statistically we should expect stronger CH^+ lines in A stars than in stars of types O and B; and third, by choosing distant stars, some of them in the Perseus arm, it is possible to ascertain whether molecular lines are interstellar and not circumstellar in case their velocity corresponds to the Orion arm.

II. Observations

The observations were made with the 120-inch reflector of Lick Observatory on January 17-20, 1968. The 40- and 80-inch cameras were used with 103 a-O baked emulsion. Seven stars were observed with the 80-inch camera, five of them at a dispersion of 2.7 Å/mm and two at 4 Å/mm. Two stars were observed with the 40-inch camera at a dispersion of 5.4 Å/mm. All the plates have intensity calibration strips and comparison spectra. The wavelength range of the 2.7 Å/mm spectra covered from $\lambda\lambda$3600 to 4280 Å (the spectra did not reach the λ4300 Å line of CH), while the other four plates covered from $\lambda\lambda$3500 to 4500 Å. The list of stars is given in Table 1, identified by their number from the Catalogue of Bright Stars (Hoffleit 1964); the second and third columns indicate the galactic longitude and latitude referred to the pole and center of the galaxy as adopted by the IAU in 1958; the fourth, fifth, and sixth columns give, respectively, spectral class, visual magnitude, and $B-V$ color from the Catalogue of Bright Stars; and the seventh column shows the plate dispersion in Ångstroms/mm.

III. Discussion

The distance modulus, y, to a star is given by

$$y = V_{obs} - R\,[\,(B-V)_{obs} - (B-V)_o] - M_v\,, \qquad (1)$$

where $(B-V)_o$ represents the intrinsic color taken from Johnson (1958), R is the ratio of total extinction in the V magnitude over the selective extinction in $B-V$ for which we will adopt 3, and M_v is the absolute visual magnitude taken from Johnson and Iriarte (1958) for the stars of luminosity class I_a and I_{ab}, and from Keenan (1963) for the stars of luminosity class I_b. The V_{obs} and $(B-V)_{obs}$ were taken from Table 1.

TABLE 1

Basic data

Star HR	l^{II} *(1900)*	b^{II} *(1900)*	*Spectral Type*	V	$B-V$	*Dispersion (Å/mm)*	*Spectroscopic Parallax (mag.)*	*Association*
9018	115° 42′	+00° 14′	A3 I_a	5.42	+0.66	2.7	10.65	18
618	132 55	−02 57	A1 I_a	5.68	+0.62	2.7	11.04	21
641	133 30	−02 37	A3 I_{ab}	6.46	+0.59	5.4	10.90	21
685	135 30	−04 48	A2 I_a	5.17	+0.37	2.7	11.26	21
964	141 34	+00 25	A0 I_a	5.91		2.7		
1035	141 29	+02 53	B9 I_a	4.23	+0.40	2.7	9.89	22
1040	142 11	+02 03	A0 I_a	4.58	+0.59	5.4	9.93	22
1804	176 46	−02 43	B9 I_b	5.65	+0.18	4.1	10.57	24
2066	181 13	+02 03	A2 I_b	6.39	+0.30	4.1	10.19	

The distance moduli expressed in magnitudes are shown in Table 1. It is difficult to estimate a probable error for these distances since the absolute magnitudes of supergiant stars are not well known but probably it does not exceed 0.5 magnitudes. The number of the association to which the star might belong is given in the last column of Table 1 (Morgan, Whitford, and Code 1953). The distance to any of these associations is better determined than the distance to a single star,

TABLE 2

Radial velocities and equivalent widths of interstellar lines

Star HR	Stellar Rad. Vel. (km/sec)	Δv (km/sec)	$\lambda3933$ Rad. Vel. (km/sec)	$\lambda3874$ Rad. Vel. (km/sec)	E. W. (mÅ)	$\lambda4232$ Rad. Vel. (km/sec)	E. W. (mÅ)
9018	−45.6a	+ 9.2	−67, −56, −24, +9, +21				
618	−36.3a	+ 3.8	−56, −11	−15.3	R (1), 7.6; R (0), 16.5; P (1), ∼4	− 7	15
641	−40.5b	+ 3.6	−55, −40*, −13				
685	−15.2b	+ 2.7	−39, −12*			− 4	6
964	−11.9b	+ 1.7	−18, −11*, −3	−16	5	−17	10
1035	− 6.8b	+ 1.9	−26, −7*	− 1	6	− 8, +5	5, 5
1040	− 6.0a	+ 1.5	−7*, +26				
1804	+16.7b	−10.0	+12			+20	15
2066	+19.0c	−10.4	+16				

* Stellar and interstellar features blended.

however the individual distances were given since a given star might not be a member of the assigned association.

The second column in Table 2 shows the stellar heliocentric radial velocity and the quality of the velocity determination as taken from the General Catalogue of Stellar Radial Velocities (Wilson 1953). In the third column the correction for solar motion, Δv, is given, where the "standard solar motion" adopted by Hulst, Muller, and Oort (1954) was used. The fourth column shows the measured heliocentric radial velocities of the interstellar calcium lines. The fifth and seventh columns contain the radial velocities of the CN and CH^+ features, respectively. The internal consistency of the interstellar radial velocities is of the order of 1 to 2 km/sec; the probable error is slightly larger for the calcium lines since they are in general strongly blended and have a stellar component; the velocity determined from the line of $\lambda4232.54$ can also be slightly affected because it is in the wing of $\lambda4233.16$ of Fe II. The *D* line velocities measured by Münch (1957) in the five stars that we have in common agree within 3 km/sec with the *H* and *K* velocities measured by us. We will also compare our observations with the observations of the $\lambda21$-cm line made with the 300-foot antenna by Westerhout (1966), who considered a strip of the sky from $b^{II} = +1$ to $-1°$, though most of our stars are either slightly above or slightly below this band they are close enough to warrant a fair comparison. The equivalent widths of the molecular lines are given in columns sixth and eighth; the estimated probable errors are of the order of 2 mÅ for the lines of 10 to 17 mÅ and of $\approx$ 1.5 mÅ for the lines of 5 to 8 mÅ.

Following is a description of the interstellar features of the spectrum of each star. A density tracing of the CN region of HR 618 is given in Figure 1. In Figure 2 the spectra of HR 618,

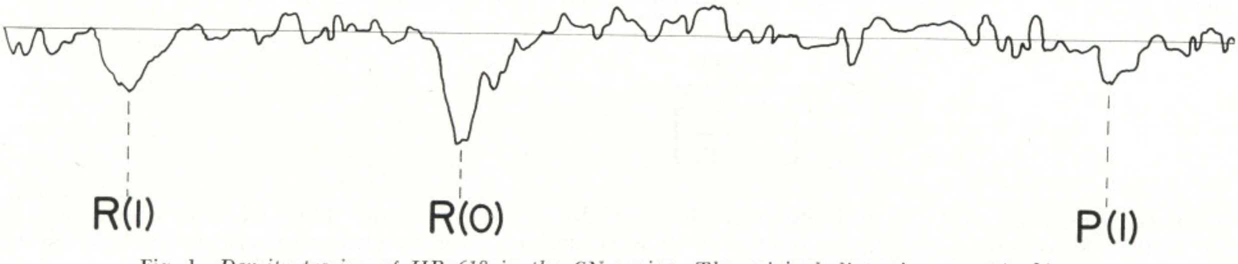

Fig. 1.—*Density tracing of HR 618 in the CN region. The original dispersion was 2.7 Å/mm.*

HR 1035, ζ Oph, and ζ Per in the Ca II region are shown. The dispersion of the original plates of ζ Oph and ζ Per is also 2.7 Å/mm. These plates were taken during the same observing run for comparison purposes.

HR 9018 (6 Cas). It is the only 2.7-Å/mm spectrogram that does not show molecular lines. This spectrogram is not as good as those of the other four stars. At least five interstellar components of the *H* and *K* lines are detected and by comparing the calcium profiles with the $\lambda21$-cm data it is clear that part of the calcium interstellar profile is formed in the Perseus arm. The velocity of the star also corresponds to that of a star in the Perseus arm. The distance modulus is somewhat

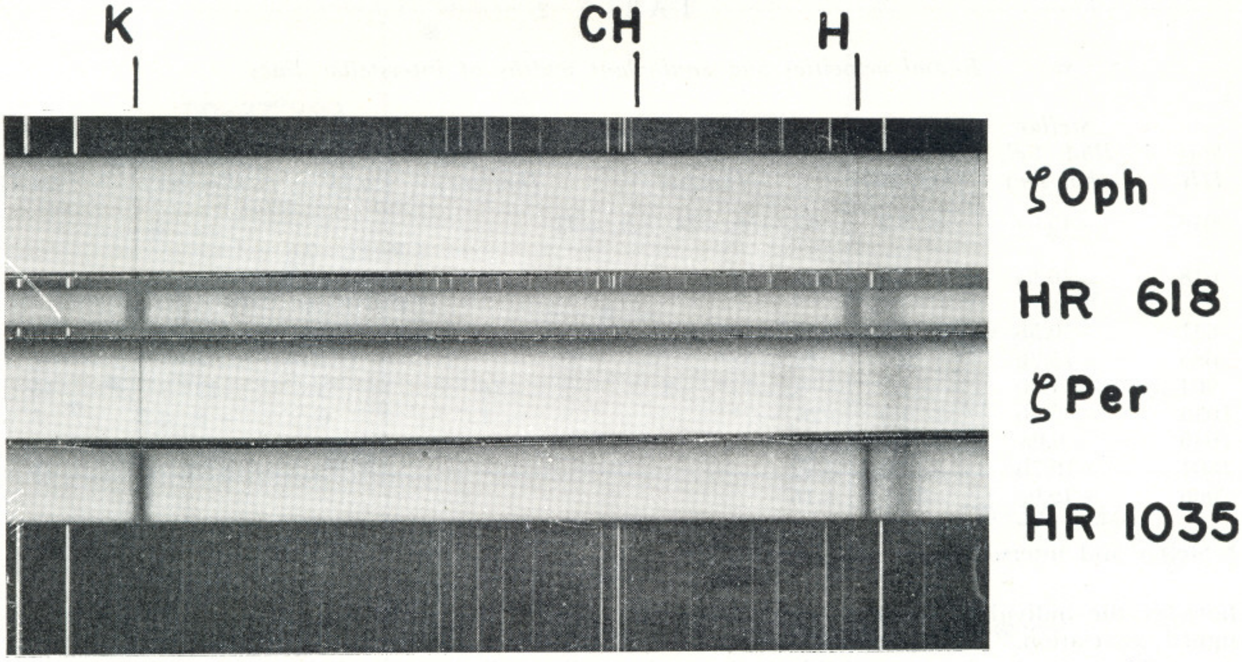

Fig. 2.—*Interstellar absorption lines of CH⁺, and Ca II.* Positive prints; the original dispersion was 2.7 Å/mm.

smaller than expected and probably the absolute luminosity of the star is higher than that listed by Johnson (1958).

HR 618. This spectrogram shows four molecular lines, three of CN and one of CH^+. The CN lines are $\lambda\lambda$3874.00, 3874.61, and 3875.77 which correspond to the R(1), R(0), and P(1) lines of the (0,0) band of the $B^2\Sigma^+ - X^2\Sigma^+$ transition. The CH^+ line λ4232.54, is the R(0) line fo the (0,0) band of the $A^1\pi - X^1\Sigma$ transition.

From the ratio of the R(1) and R(0) lines of CN it is possible to obtain the relative populations of the excited and the ground levels under the assumption that the lines are not saturated,

$$\frac{N_1}{N_o} = \frac{g_1}{g_o} e^{-\Delta E/kT_E} = \frac{\lambda_o^2}{\lambda_1^2} \frac{f_o}{f_1} \frac{W_1}{W_o}, \qquad (2)$$

where the subscript 1 refers to the R(1) line and 0 to the R(0) line, $\Delta E = 5.466$ °K (Herzberg 1950), $g_1/g_o = 3$, and $f_1/f_o = 2/3$ (McKellar 1941). From equation (2) we obtain

$$T_E = \frac{-5.466}{ln\left[\frac{1}{2}\frac{W_1}{W_o}\right]}. \qquad (3)$$

From equations (2) and (3) and the equivalent widths of λ3874.0 and λ3874.61 the values $T_E \approx 3.7 \pm 0.7$ °K as well as $N_1/N_o = 0.69 \pm 0.20$ were derived. Due to saturation effects the real excitation temperature is smaller than that derived in equation (3). However the saturation cannot be very large because the P(1) line of CN, λ3875.77, in the unsaturated case should be half the intensity of the R(1) line, and the intensity ratio is indeed close to that value. The effect of saturation cannot be estimated since the lines are very weak and the probable errors of the equivalent widths are large. More plates are needed to lower the probable error of the temperature determination and to estimate the degree of saturation by means of the P(1) line.

By comparing the calcium and the 21-cm profiles it is clear that the Orion arm and part of the Perseus arm are seen projected on *HR 618;* the velocity of the star is close to the velocity expected for an object in the Perseus arm. *HR 618* is approximately 4° from *W* 3 and *W* 4 but in a direction completely free of H II regions, the spectroscopic distance to the star is about 1.6

kpc and the kinematic distance of *W* 3 and *W* 4, that belong to the Perseus arm, is 3.2 kpc (Dieter 1967); the main part of this difference is probably due to inherent errors in the two types of distance determinations, but the three objects are expected to be roughly at the same distance.

From the difference in radial velocities it seems that the CH^+ originates in one cloud and the CN in another.

HR 641. Again by comparing the λ21-cm and the calcium line profiles it is clear that this star belongs to the Perseus arm, the velocity of the star corresponds to an object in that spiral arm, and the spectroscopic distance is similar to the other three stars that belong to the Perseus arm, namely, *HR 9018, HR 618,* and *HR 685.*

HR 685 (9 Per). From the spectroscopic parallax and the calcium features it can be said that this

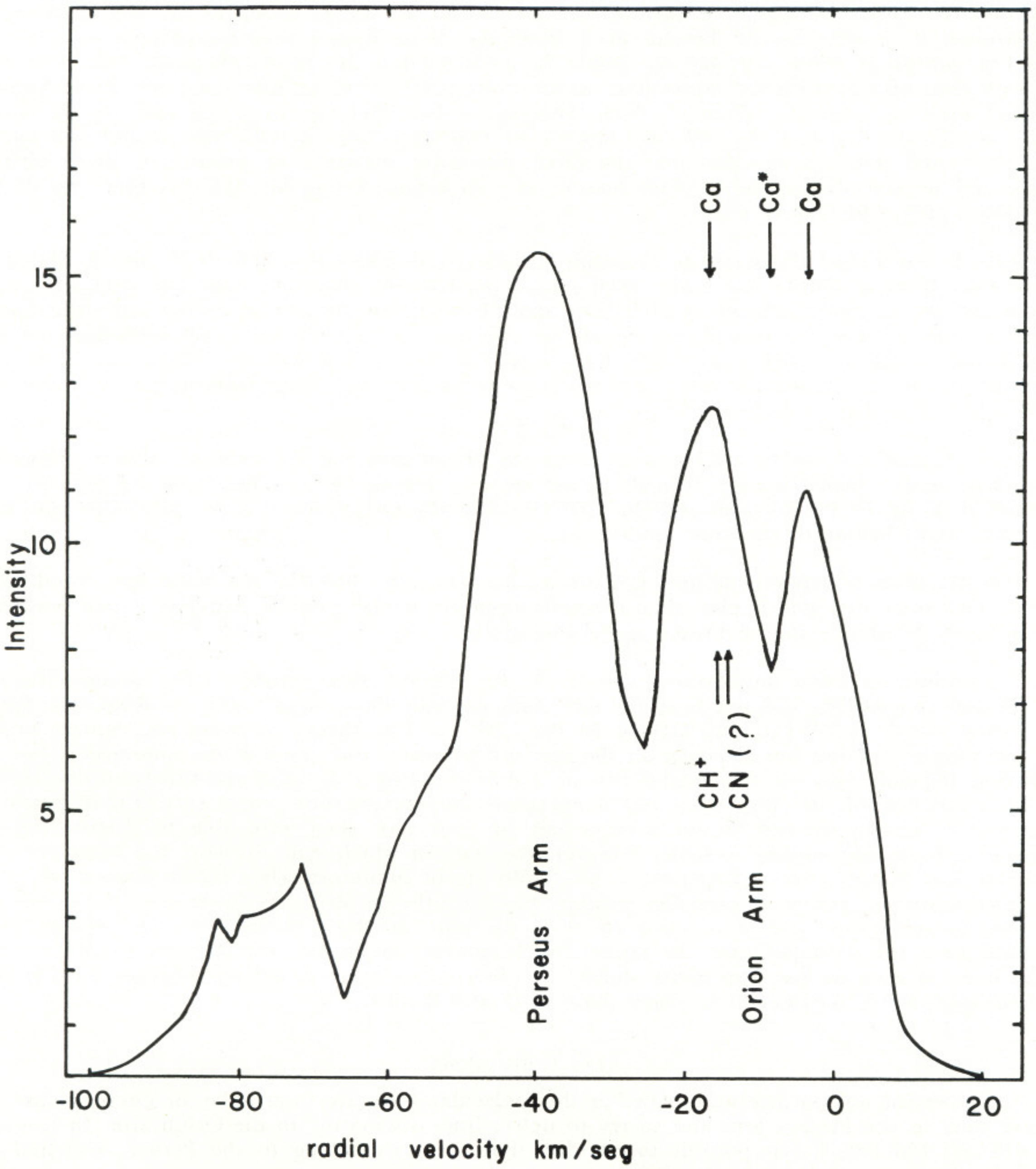

Fig. 3.—*Velocity profile of the 21-cm line in the direction of* $l^{II}(1950) = 141.°49$, $b^{II}(1950) = +\ 00°25'$. *The intensity scale is that of Westerhout (1966). The arrows mark the central radial velocities of the interstellar components, see Table 2.*

star is in the Perseus arm. Its velocity is smaller than expected which might be due to a peculiar velocity. *HR 685* shows a faint CH^+ line whose velocity corresponds to that of the Orion arm.

HR 964. We do not have an observed value of $B-V$ therefore we do not have a spectroscopic parallax, but by comparing the calcium and λ21-cm profiles it can be said that it is in the Orion arm. In Figure 3 we show the λ21-cm profile in the direction of this star, the main feature originates in the Perseus arm and the Orion arm shows two components. The calcium features in our spectrogram are clearly related to the Orion arm and no interstellar features that could be attributed to the Perseus arm are observed. The spectrum shows a very well defined line of CH^+, there is also a very faint feature that we think is a CN line since in that case its velocity would be almost the same as that of CH^+ as well as of a maximum of the 21-cm profile.

HR 1035. We believe this star is located in the Orion arm since the spectroscopic parallax is definitely smaller than that of stars assigned to the Perseus arm: the velocity of the star also agrees with that of the Orion arm; the feature at −26 km/sec is not as strong as an arm feature; and furthermore, if it were in the Perseus arm, from the 21-cm data a velocity component in the calcium line profile at about −40 km/sec would be expected but this is not observed. *HR 1035* shows the R(0) line of CN with an equivalent width of 6 mÅ; the R(1) line does not show, however, an upper limit of 3 mÅ was obtained. With these two values and equations (2) and (3) we derived $N_1/N_o < 0.77$ and $T_E < 4$ °*K*. *HR 1035* also shows two faint lines of CH^+ at −8 and +5 km/sec. From the radial velocities it seems that the three molecular features are formed in three different clouds, and by considering the calcium feature at −26 km/sec it can be said that there are at least four clouds along the line of sight.

HR 1040. It has almost the same spectroscopic parallax and velocity as *HR 1035*, and is about one degree away from it. Unlike the other seven stars reported here, there are some light nebular patches of emission in the neighborhood of *HR 1040* and *HR 1035* and though we do not know the distance at which these patches are located, they could be associated with both stars. *HR 1040* does not show the calcium feature at −26 km/sec, instead it shows a feature at +26 km/sec. Unfortunately the plate dispersion is only 5.4 Å/mm therefore it is not possible to ascertain if the molecular clouds appearing in *HR 1035* extend to *HR 1040.*

HR 1804. This star could be farther away than the Orion arm but its location, almost opposite to the galactic center, makes it very difficult to use velocity arguments to determine its distance. *HR 1804* might be in the Perseus arm and the CH^+ cloud in the Orion arm but the possibility also exists that both might belong to the same spiral arm.

HR 2066. We observe only one definite calcium feature which is a blend of the stellar and instellar components and since this star is also almost exactly opposite to the galactic center it is not possible to determine if the star is in the Orion or Perseus arms.

According to Bates and Spitzer (1951), A stars should show stronger CH^+ circumstellar lines than O and B stars. We did not find any CH^+ line stronger than those found by Rogerson, Spitzer, and Bahng (1959) in 20 Tau (B7 III) or 55 Per (B7 V). The theory of Bates and Spitzer predicts that the intensity of the line depends on the star temperature and not on its luminosity, but this prediction depends also on the availability of a dust cloud near the star, and this condition in itself can be a function of the luminosity and temperature. Supergiant stars evolve very fast, in particular, A stars were recently stars of O and B types and in their past they were able to destroy the dust clouds in a large surrounding volume; however, the stars in which some support has been found for the Bates and Spitzer thesis (Rogerson, *et al.* 1959) are of luminosity class III or fainter, which not only have destroyed grains in a smaller volume, but since they evolve at a slower pace the grains have had time to get formed and/or to move closer to the stars. In short, if the Bates and Spitzer theory is corerct for a given temperature, the fainter the luminosity of the star the stronger the CH^+ circumstellar lines. A stars of low luminosity should be observed to try to determine whether the CH^+ lines in their spectra are statistically stronger than in O and B stars.

IV. Conclusions

A powerful way to determine whether the molecular lines are interstellar or circumstellar is to observe stars in the Perseus arm and to try to detect lines originating in the Orion arm. In two cases, *HR 618 and HR 685,* it was possible to establish that the stars belong to the Perseus arm and that the molecular lines originate in the Orion arm.

In order to study to what extent the molecular features are associated with H II regions, more

A stars should be observed; however from our data it can be said that such association is not generally the case.

To obtain very precise determinations of the excitation temperature of the CN lines not only is it necessary to have high dispersion spectra, but also to select stars that show CN lines definitely not circumstellar, in order to avoid any contribution to the excitation arising from fluorescence or proton collisions.

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REFERENCES

Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Bates, D. R. and Spitzer, L. 1951, *Ap. J.*, **113**, 441.
Clauser, J. F. and Thaddeus, P. 1967. *Proceedings of the Third Texas Symposium on Relativistic Astrophysics*, (To be published).
Dicke, R. H., Peebles, P.J.E., Roll, P. G., and Wilkinson, D. T. 1965, *Ap. J.*, **142**, 414.
Dieter, N. 1967, *Ap. J.*, **150**, 435.
Field, G. B. and Hitchcock, J. L. 1966, *Ap. J.*, **146**, 1.
Gamow G., 1948, *Nature*, **162**, 680.
——— 1956, *Vistas in Astronomy*, Vol. **2**, A Beer, ed. (Pergamon Press), p. 1726.
Herzberg, G. 1950, *Spectra of Diatomic Molecules* (New York: D. van Nostrand & Co.), p. 520.
Hoffleit, D. 1964, *Catalogue of Bright Stars* (Yale University Observatory).
Hulst, H. C. van de, Muller, C. A., and Oort, J. H. 1954, *B. A. N.*, **12**, 117.
Johnson, H. L. 1958, *Lowell Obs. Bull.*, **4**, 37, (No. 90).
Johnson, H. L. and Iriarte, B. 1958, *Lowell Obs. Bull.*, **4**, 47, (No. 91).
Keenan, P. C. 1963, *Basic Astronomical Data*, K. Aa Strand, ed. (Chicago: Univ. of Chicago Press), p. 78.
McKellar, A. 1941, *Pub. Dom. Ap. Obs.*, **7**, 251.
Morgan, W. W., Sharpless, S., and Osterbrock, D. E. 1952, *A. J.*, **57**, 3.
Morgan, W. W., Whitford, A. E., and Code, A. D. 1953, *Ap. J.*, **118**, 318 .
Münch, G. 1953, *Pub. A. S. P.*, **65**, 179.
——— 1957, *Ap. J.*, **125**, 42.
——— 1964, *Ap. J.*, **140**, 107.
Penzias, A. A. and Wilson, R. W. 1965, *Ap. J.*, **142**, 419.
Rogerson, J. B., Spitzer, L., and Bahng, J. D. 1959, *Ap. J.* **130**, 991.
Sharpless, S. 1959, *Ap. J. Suppl.*, **4**, 257.
Thaddeus P. 1968, Private communication.
Thaddeus, P. and Clauser, J. F. 1966, *Phys Rev. Letters*, **16**, 819.
Westerhout, G. 1966, *Maryland-Green Bank Galactic 21-cm Line Survey, Univ.* of Maryland.
Wilson, R. E. 1953, *General Catalogue of Stellar Radial Velocities* (Carnegie Institution of Washington).