ON THE ABUNDANCE OF INTERSTELLAR BERYLLIUM*

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ABSTRACT

A search for the ultraviolet *Be* II lines on high-dispersion spectra of χ^2 Ori and ζ Per yields negative results. The resultant upper limits on $N(Be\,\text{II})$, the number of *Be* II ions in the line of sight, combined with the values of $N(Na\,\text{I})$, found from the ultraviolet *Na* doublet, yield an upper limit of about 2×10^{-3} for $N(Be\,\text{II})/N(Na\,\text{I})$. To find the over-all *Be/Na* ratio, this upper limit must be decreased by the ratio $N(Na\,\text{I})/N(Na\,\text{II})$, whose value will depend on whether the absorbing cloud is an *H* I or an *H* II region. The assumption that the ratio of gas to dust is the same in these clouds as in the Galaxy at large makes it possible to compute the number of *H* atoms in the line of sight from the observed color excess. This computed number is an order of magnitude too great for an *H* II region, in view of the absence of any interstellar Balmer emission from the neighborhood of these stars. Analysis of conditions in an *H* I region shows that $N(Na\,\text{I})/N(Na\,\text{II})$ is probably about 2×10^{-2}, and the ratio $N(Be)/N(Na)$ becomes less than about 4×10^{-5}. This low value is about an order of magnitude less than the mean of the values found in the sun or in meteorites. The ratio $N(Ca)/N(Na)$ is also believed to be less in the interstellar gas than in the sun and in meteorites by a factor of about 40. Possibly both *Ca* and *Be* atoms, to a greater extent than *Na* atoms, may be locked up in grains.

Several years ago a search for interstellar *Li* and *Be* (Spitzer 1949) yielded negative results but led to an upper limit on the *Be/Na* ratio about equal to the relative abundance of these elements in meteorites. Additional observational material has now been obtained for the two stars ζ Per and χ^2 Ori with higher dispersion than was used previously. While the *Be* II lines at λ 3130.42 and λ 3131.06 were again not observed, the upper limit on the *Be/Na* ratio is now considerably reduced.

I. OBSERVATIONS

The plates, which were taken at the coudé focus of the 100-inch telescope, showed the *Na* I ultraviolet lines at λ 3302.34 and λ 3302.94. To determine upper limits on the ratio of *Be* to *Na*, the equivalent widths of these *Na* lines were measured in the two stars. The results are shown in Table 1. For χ^2 Ori the equivalent widths found here differ somewhat from those obtained by Dunham (1939), who found 0.060 A and 0.040 A for these two lines.

To determine an upper limit on the equivalent widths of the *Be* II lines in χ^2 Ori, the following procedure was used. A parabolic profile of about the same width as that observed for the ultraviolet *Na* lines (0.3 A) was assumed, and this profile was fitted to the tracing at the expected position of each *Be* II line and with the greatest depth consistent with the tracing. The upper limits obtained in this way were 0.018 A for λ 3131.06 and 0.015 A for λ 3130.42.

For ζ Per a different procedure was followed. On each of the two 114-inch plates a faint, sharp, presumably interstellar line could be seen some 12 A longward of the *Be* II doublet. Since this line was near the margin of visibility, its equivalent width was taken as an upper limit for the equivalent width of either of the two *Be* II lines. This procedure for determining an upper limit is perhaps more definite and less subject to criticism than the procedure used for χ^2 Ori. Measures on the tracings gave an equivalent width of 0.0052 A for this line on Plate 8410, and 0.0076 A on Plate 8418, averaging

* This article is based on observations made by the senior author as guest investigator at the Mount Wilson and Palomar Observatories.

0.0064 A. If the procedure used for χ^2 Ori were used for ζ Per, the upper limit found would be somewhat less than 0.0064 A.

The identification of this sharp absorption line in the spectra of ζ Per is itself a problem. The measured wave length, corrected for the earth's motion, is 3143.35 A, with virtually identical results for the two plates. If the interstellar clouds in the direction of ζ Per are assumed to have a velocity of +12.0 km/sec, the value obtained by Adams (1949) for K and H, the wave length of this line corrected for the Doppler shift of the cloud becomes 3143.22 A. An *Fe* I ultimate line at 3143.24 A might be a reasonable identification. Unfortunately, the line λ 3193.21, another ultimate line in the same multiplet, does not appear on either of the two high-dispersion plates of ζ Per. According to R. B. King and A. S. King (1938), the f-value of λ 3193.21 is ten times that for λ 3143.24. Failure of the stronger line to appear would seem to rule out the identification of this sharp, presumably interstellar feature as a line of neutral *Fe*. Lines of interstellar molecules are relatively strong in ζ Per, and λ 3143.2 may perhaps be a molecular feature.

TABLE 1

EQUIVALENT WIDTHS OF ULTRAVIOLET *Na* LINES

STAR	PLATE NO.	CAMERA	W FOR	
			λ 3302.34	λ 3302.94
χ^2 Ori.......	8526	73-in.	0.075 A	0.037 A
ζ Per	8348	73-in.	.030	.014
	8410	114-in.	.028	.015
	8418	114-in.	.024	.019
	Mean	....	0.027	0.017

II. NUMBER OF ABSORBING ATOMS

The observations give directly an upper limit on the ratio $N(Be\,\textrm{II})/N(Na\,\textrm{I})$, where N is the number of atoms in the line of sight, per square centimeter. For unsaturated lines the equivalent width W is given by

$$W=\frac{\pi N e^2\lambda^2 f}{m c^2}, \tag{1}$$

where W and λ are both measured in centimeters, f is the upward oscillator strength, and other symbols have their usual meanings. Equation (1) may be applied to the *Be* II lines, and also to the ultraviolet *Na* lines in χ^2 Ori.

For the *Na* I ultraviolet lines in ζ Per, equation (1) must be modified slightly to take into account the effects of saturation, indicated by the doublet ratio less than 2.0. The theory of the equivalent width for Doppler-broadened lines has been given by Ladenburg (1930); Strömgren (1948) has given the appropriate functions in a table (Table 2 in his paper) suitable for numerical computations. With the measured value of the doublet ratio, the number of absorbing atoms may be obtained. If the true doublet ratio is substantially less than the measured value, 1.59, which might be anticipated for a single, dense, and relatively quiescent *H* I cloud, $N(Na\,\textrm{I})$ in the line of sight to ζ Per will exceed the value given in Table 2, and the upper limit on $n(Be)/n(Na)$ will be decreased.

The f-values needed have been measured, for the *Na* ultraviolet lines, by Filippov and Prokofjew (1929); they find values of 0.0094 and 0.0047 for the stronger and weaker lines, respectively, in the doublet. For the resonance lines of *Be* II no detailed computations or measures are apparently available. For the corresponding resonance lines in *Mg* II and *Ca* II the theoretical *f*-values are (Biermann 1950) 0.92 and 1.19; these values include both lines in the doublet. A similar rise in *f*-value with increasing atomic number is shown by the corresponding sequence of resonance lines of *Li* I, *Na* I, and *K* I, for which the reported *f*-values (Biermann 1950) are 0.71, 1.00, and 1.05. An *f*-value of about 0.75 for the *Be* II doublet seems reasonable; accordingly, *f* has been set equal to 0.50 for λ 3130.42 and to 0.25 for λ 3131.06. The resultant values of *N* are given in Table 2.

III. TOTAL NUMBER OF ATOMS

To obtain an upper limit on the ratio of beryllium to sodium in the interstellar gas, the ratios given in Table 2 must be corrected for the number of atoms in other states of ionization. The ionization equilibrium will depend on the first and second ionization potentials, which are 9.3 and 18.1 volts, respectively, for *Be;* 5.1 and 47.1 volts for *Na;* and 6.1 and 11.8 for *Ca*. We shall carry out separate analyses on the two assumptions: (*a*) the material producing the interstellar lines is an *H* I cloud (hydrogen neutral), and

TABLE 2

NUMBER OF ATOMS IN LINE OF SIGHT

	N (*Be* II)	*N*(*Na* I)	*N*(*Be* II)/ *N*(*Na* I)
χ^2 Ori....	3.5×10^{11} cm^{-2}	8.2×10^{13} cm^{-2}	4.3×10^{-3}
ζ Per....	1.4×10^{11}	5.0×10^{13}	2.8×10^{-3}

(*b*) the material is an *H* II region (hydrogen ionized). We shall draw heavily here on Strömgren's (1948) analysis of ionization equilibrium in the interstellar gas.

a) H I CLOUD

If the hydrogen is neutral, there will be essentially no radiation shortward of 13.5 ev, and no *Be* III will be present. The ratio $n(Be\text{ II})/n(Be\text{ I})$ will be considerably greater than unity; it is evident from Strömgren's analysis that $n(Ca\text{ III})/n(Ca\text{ II})$ is usually greater than unity, and *Be* I, with a lower ionization potential and a higher *f*-value for the bound-free transition from the ground state, should be ionized more readily than *Ca* II. We shall therefore set $n(Be)$, the number of *Be* atoms per cubic centimeter, in all stages of ionization, equal to $n(Be\text{ II})$.

The ratio of *Na* I to *Na* II may be found from the result by Strömgren (1948) for a kinetic temperature of 100° K,

$$\frac{n\,(Na\text{ I})}{n\,(Na\text{ II})}=0.60n_e\,. \tag{2}$$

If we assume, with Strömgren, that the relative abundances of the elements in the interstellar gas are about the same as in stars, we may set n_e equal to about 200 $n(Na\text{ II})$. Also $N(Na\text{ I})$, the number of neutral sodium atoms in the line of sight, may be set equal to $n(Na\text{ I})d$, where *d* is the thickness of the cloud producing the observed lines. Equation (2) then yields the values in Table 3.

Since $n(H)/n_e$ is probably at least 2000 in an *H* I cloud (if *H* atoms in H_2 molecules are included in $n[H]$), a value of *d* as low as 0.1 parsec corresponds to a very high cloud density, at least 500 atoms/cm³. So small a cloud seems improbable, and we may tentatively assume that *d* is 10 parsecs. Further evidence for this assumption will be given later. On this basis, the upper limits on $n(Be)/n(Na)$, found on combining the results in Tables 2 and 3, become 7.3×10^{-5} in χ^2 Ori and 3.9×10^{-5} in ζ Per. These values may be compared with the corresponding ratios of 6.3×10^{-4} in meteorites—according to Urey (1952)—and 1.5×10^{-4} in the sun—according to Greenstein and Tandberg-Hanssen (1954). The solar value is based on an assumed ratio of 2.5 for $n(Ca)/n(Na)$.

b) *H* II CLOUD

In this case *Be* II can be ionized to *Be* III. However, comparison with Strömgren's results for *Ca* and consideration of the 6.5-volt difference in ionization potential between *Ca* II and *Be* II indicate that, for the electron densities of interest, $n(Be\ \text{III})/n(Be\ \text{II})$ will be small. As in *H* I regions, $n(Be\ \text{I})/n(Be\ \text{II})$ will also be small, and we may again set $n(Be)$ equal to $n(Be\ \text{II})$.

TABLE 3

RELATIVE IONIZATION OF SODIUM IN *H* I REGIONS

d (PARSECS)	χ^2 ORI		ζ PER	
	n_e	$n(Na\ \text{I})/n(Na\ \text{II})$	n_e	$n(Na\ \text{I})/n(Na\ \text{II})$
0.1	2.9×10^{-1} cm^{-3}	1.7×10^{-1}	2.3×10^{-1} cm^{-3}	1.4×10^{-1}
1	9.2×10^{-2}	5.5×10^{-2}	7.3×10^{-1}	4.4×10^{-2}
10	2.9×10^{-2}	1.7×10^{-2}	2.3×10^{-2}	1.4×10^{-2}

TABLE 4

RELATIVE IONIZATION OF SODIUM IN *H* II REGIONS

d	0.1 Parsec	1 Parsec	10 Parsecs
n_e	<50 cm^{-3}	<15.8 cm^{-3}	<5.0 cm^{-3}
$n(Na\ \text{I})/n(Na\ \text{II})$	<1.0	<0.30	<0.10

The ratio of *Na* I to *Na* II in an *H* II region at 10,000° K, according to Strömgren, is

$$\frac{n\ (Na\ \text{I})}{n\ (Na\ \text{II})} = 0.019 n_e\,. \tag{3}$$

The product of n_e^2 and the thickness of the cloud, in parsecs, is called the "emission measure." According to Sharpless and Strömgren,[1] the emission measure in the line of sight to χ^2 Ori and ζ Per does not exceed 250 in either case. We thus obtain upper limits both for n_e and for $n(Na\ \text{I})/n(Na\ \text{II})$, as given in Table 4.

Again a cloud as small as 0.1 parsec in thickness seems very improbable. At a density comparable with 5cm^{-3}, such a cloud would expand at roughly the sound velocity of about 20 km/sec and would double its radius in 5000 years. Even a cloud 1 parsec across seems unlikely. We shall take 0.1 as a reasonable upper limit for $n(Na\ \text{I})/n(Na\ \text{II})$ in *H* II regions.

We see that in this case the ratio of *Be* to *Na* in the interstellar gas is less than about 3×10^{-4}, unless the clouds producing the observed lines in χ^2 Ori and ζ Per turn out

[1] We are much indebted to Drs. Sharpless and Strömgren for permission to use their unpublished results.

to be unexpectedly dense. This upper limit is less than the value observed in meteorites but greater than the value found in the sun. In view of the many uncertainties, one may in this case conclude only that the abundance of *Be* relative to *Na* is no greater in interstellar space than it is in meteorites.

IV. RATIO OF GAS TO DUST

Evidently, a consideration only of observed equivalent widths and computed ionization conditions does not yield a very low upper limit on the *Be*/*Na* ratio, because of uncertainty as to whether or not *H* is ionized, in addition to uncertainty as to cloud size. However, the measured color excesses of χ^2 Ori and ζ Per yield additional information on the interstellar medium, which we may now take into account.

Specifically, if the ratio of gas to dust is assumed to be roughly constant throughout the Galaxy, a definite decision can be made between the assumptions of *H* I and *H* II regions in the line of sight to these stars. This assumption of uniformity is theoretically plausible and is supported, moreover, by recent measurements of *H* emission at 21 cm.

TABLE 5

DENSITY OF HYDROGEN IN χ^2 ORI CLOUD

Source of Information	$n(H)$ for Cloud of Thickness:		
	0.1 Parsec	1 Parsec	10 Parsecs
Color excess	7500 cm^{-3}	750 cm^{-3}	75.0 cm^{-3}
$N(Na$ I), *H* I region assumed	580	180	58.0
Emission measure, *H* II region assumed	<50	<16	<5.0

Lilley (1954) has shown that regions of high 21-cm emission at galactic latitudes of $-15°$ coincide with regions of high optical extinction. If we accept this assumption, then $N(H)$, the number of *H* atoms (including those in H_2 molecules) in the line of sight to a star, is a linear function of E_1, the photoelectric color excess of the star. According to Stebbins, Huffer, and Whitford (1940*b*), the mean increase of E_1 per kiloparsec is 0.26. Since the mean density of *H* atoms per cubic centimeter in the galactic plane is about 1, we have

$$N(H) = 1.2 \times 10^{22} E_1 . \tag{4}$$

The same value of $N(H)/E_1$ is found from the detailed correlation of extinction and 21-cm emission observed by Lilley (1954).

The density of *H* atoms per cubic centimeter in a cloud of thickness *d* equals simply $N(H)/d$. For χ^2 Ori, E_1 is 0.19, according to Stebbins, Huffer, and Whitford (1940*a*). The values of $n(H)$ found from equation (4) are shown in Table 5. Also shown are the corresponding densities computed for an *H* I cloud in the line of sight to χ^2 Ori, found from Table 3 on the assumption that $n(H)$ equals 2000 n_e, and for an *H* II cloud found from Table 4 with the obvious assumption that n_e equals $n(H)$. For ζ Per the results are closely similar, since the color excess for this star is 0.17.

While the computed densities for *H* I regions are somewhat hypothetical, relying as they do on assumed ratios of n_e to $n(Na)$ and of n_e to $n(H)$, the upper limits on the *H* densities in an *H* II region are rather direct results of the low emission measure for these regions. Evidently, the assumption of an *H* II cloud in the line of sight to these stars is grossly inconsistent with a uniform ratio of gas to grains. To reconcile the high color excess with the observed absence of Balmer emission requires a ratio of grains to gas a full order of magnitude greater than is found elsewhere in the Galaxy. Such an extreme condition seems implausible, though it cannot be excluded. Assumption of several clouds in the line of sight does not alter the situation appreciably, since most of the clouds must be *H* I regions, to avoid large Balmer emission, and the ultraviolet *Na* lines will be produced with about the strength observed.

While the assumption of an *H* II cloud may therefore be excluded, at least tentatively, very small *H* I clouds also seem ruled out by the values in Table 5. A cloud thickness of 10 parsecs, which seems most likely in any case, provides the best agreement between the different values of n (*H*). For this value of the cloud thickness we have already seen that the *Be*/*Na* ratio becomes less than about 5×10^{-5}, about a third of the value found in the sun and a fifteenth of the value observed in meteorites. Since the adopted upper limits are believed to be conservative, the actual *Be*/*Na* ratio in the interstellar gas is probably appreciably less than 5×10^{-5} and we may conclude that the ratio of *Be* to *Na* in the interstellar gas is probably an order of magnitude less than in the solar system and in stars generally.

V. DISCUSSION OF RESULTS

At one time it was thought likely that if the interstellar gas were primordial and had never been heated to thermonuclear temperatures, the relative abundance of *Be* in interstellar space might be higher than elsewhere. The present discussion suggests precisely the opposite result, with a relative *Be* abundance less in interstellar space than anywhere else. This unexpected conclusion cannot be regarded as established, since it rests on the assumption that the ratio of gas to dust is about the same in different clouds. In addition, uncertain assumptions as to the chemical composition of the interstellar gas enter into the precise result. However, the weight of existing evidence seems to favor the tentative conclusion that the *Be*/*Na* ratio is definitely less in the interstellar gas than in the sun and the meteorites.

This result is perhaps related to the conclusion by Strömgren (1948) that the *Ca*/*Na* ratio for the interstellar gas appears to be less by a factor of 40 than the corresponding ratio for meteorites. The atoms of *Ca* and *Be* are chemically similar, and any influence affecting one might also affect the other.

It is difficult to believe that the abundance of *Ca* and *Be* nuclei is much less in the interstellar medium as a whole than in the solar system and in the stars. Such a difference would be most difficult to account for theoretically. However, if *Ca* and *Be* are primarily concentrated in the interstellar grains, while *Na* atoms are mostly in the gaseous phase, the observed abundance differences are readily explained. As suggested by Spitzer (1954), surface photodissociation of atoms from grains might well be markedly different for different atoms and could perhaps account for different fractions of atoms being "locked up" in the grains. Such physical mechanisms are still somewhat speculative, but the possibility that both *Be* and *Ca* atoms are preferentially concentrated in the grains rather than in the interstellar gas would seem to offer a reasonable working hypothesis, consistent with presently known data.

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