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ON THE POSSIBILITY OF OBSERVING INTERSTELLAR ALUMINUM

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ABSTRACT

Of the interstellar ions which might be expected to be observed, only Al^0, Co^+, and Ni^+ remain undetected. Theoretical estimates of the equivalent widths of λ 3944 of Al I in the spectra of χ^2 Ori and ζ Per have been made, using a photoionization cross-section derived by the quantum-defect method. The predicted width in ζ Per is between 0 9 and 2.7 mA, depending on the importance of autoionization; these values are not inconsistent with a recent observational upper limit. An appendix treats quantitatively the excitation of fine structure in interstellar space. While the results indicate that even very low-lying levels, such as that of Al^0, are strongly depopulated, attention is drawn to the importance of excitation by collisions with H atoms.

I. INTRODUCTION

Interstellar atomic absorption lines arise from the ground levels of abundant elements whose ionization states are sufficiently favorable. If one defines as "abundant" any element having more than 10^{-7} times the abundance of hydrogen, a list of "observable ions" would include Na^0, Al^0, K^0, Ca^0, Ca^+, Ti^+, Fe^0, Co^+, and Ni^+. Of these, only Al^0, Co^+, and Ni^+ have not yet been found (Biermann 1950). The latter two ions should be the dominant ionization states of Co and Ni and, on the basis of cosmic abundances, should give lines comparable in strength to those of Ti^+. That such are not observed is probably the result of exceptionally low f-values. The case of Al^0 is particularly interesting, as the f-value of Al I λ 3944 is known theoretically to be fairly large. This, coupled with its large abundance (exceeding that of sodium), leads us to expect that it can be detected in interstellar absorption. In what follows we calculate equivalent widths of λ 3944 in two stars, having recourse to the theory of the Al^0–Al^+ ionization equilibrium.

The line of interest, λ 3944.018, is a $3\ ^2P^o_{1/2}$–$4^2S_{1/2}$ transition from the ground level of Al^0; it has an f-value equal to 0.066 according to the calculations of Biermann and Lübeck (1948). We may assume, in accordance with the results of the appendix, that practically all Al atoms are in the ground level, even though the $^2P_{3/2}$ level is only 0.014 ev above ground. However, most Al atoms will be singly ionized in an H I region, the first and second ionization potentials being 5.98 and 18.82 ev. The equivalent width depends directly on the ionization equilibrium, being inversely proportional to the ionization function, I = (ions) (electrons) (atoms)$^{-1}$.

For numerical purposes it is convenient to compare the equivalent width of λ 3944

with that of the weak line, Na I λ 3302. This is particularly appropriate because Na is similar to Al in ionization potentials and therefore is also predominantly singly ionized. If W is the equivalent width (in A) and N is the elemental abundance,

$$\frac{W(3944)}{W(3302)} = \frac{N(\mathrm{Al})}{N(\mathrm{Na})} \frac{(3944)^2}{(3302)^2} \frac{f(3944)}{f(3302)} \frac{I(\mathrm{Na})}{I(\mathrm{Al})} = 25.9 \frac{I(\mathrm{Na})}{I(\mathrm{Al})}. \quad (1)$$

We have taken the abundance ratio from Suess and Urey (1956) to be 2.16 and the f-value of λ 3302 to be 0.0094 from the experiments of Filippov and Prokofjew (1929); both lines are assumed weak. As λ 3302 has been seen in several stars, equation (1) makes it clear that the only reason that λ 3944 has not been seen is a much larger I for Al than for Na. As we shall see, the former is fairly normal, while the latter is well known to be abnormally small.

II. THE ALUMINUM IONIZATION EQUILIBRIUM

Seaton (1951) writes $I = \Gamma/a$, where

$$\Gamma = c\,h^{-1} \int_{\nu_1}^{\infty} a_\nu^1 \rho_\nu \nu^{-1} d\nu \quad (2)$$

is the rate of ionization per second by stellar radiation of density ρ_ν, and

$$a = \left(\frac{2}{\pi}\right)^{1/2} c^{-2} (m k T_e)^{-3/2} \sum_{n=1}^{\infty} \frac{\varpi_0^n}{\varpi_+^1} \exp\left(\frac{\chi^n}{kT_e}\right) \int_{h\nu=\chi^n}^{\infty} a_\nu^n \exp\left(-\frac{h\nu}{kT_e}\right) (h\nu)^2 d(h\nu), \quad (3)$$

is the rate of electron capture per second per unit electron density. In the present calculations we have used the ρ_ν calculated by Lambrecht and Zimmermann (1956), taking account of model atmospheres and including the effects of interstellar absorption; they neglected the contribution of Sirius.

We have made an attempt to obtain an accurate value of a_ν^1, as it establishes the ionization rate through equation (2). The quantum-defect method of Burgess and Seaton (1958, 1959) was used, taking account of the factor $\zeta = 1 + \partial\mu/\partial\nu$ (Seaton

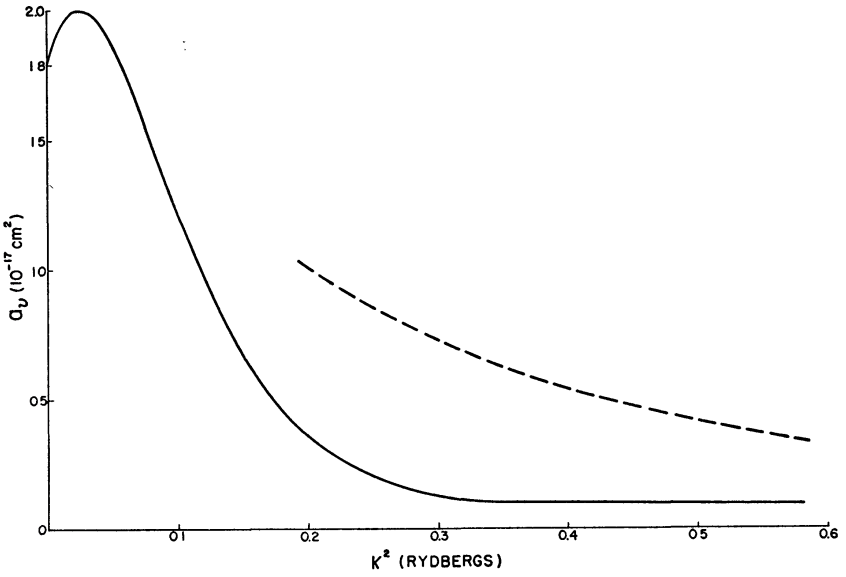

FIG. 1.—The ground-state photoionization cross-section of Al^0 as a function of electron energy (k^2) in rydbergs. The full line is the best estimate; the dashed line is an upper limit.

1958*a*) in the normalization of the bound-state wave functions. The resulting a_ν^1 is shown in Figure 1, plotted against k^2, the electron energy in rydbergs. It is felt that the data are accurate up to $k^2 = 0.1$; beyond that, there is uncertainty, owing to the difficulty of extrapolating quantum defects for the *d*-series. It is quite unlikely that the true curve is above the dashed line of Figure 1. In the course of this work Professor A. G. Shenstone pointed out that the ^{2}D term of Al^0 at 32436 cm^{-1} is very probably 3s3p^2 rather than 3s^{2}3d, since omitting it from the *d*-series shows the latter to be a normal perturbed series, repelled by the 3s3p^2 ^{2}D term. Comparisons within the isoelectronic sequence Al^0, Si$^+$, and P^{++} confirm this interpretation. It follows, incidentally, that the *f*-value of λ 3082 calculated by Biermann and Lübeck (1948) is therefore incorrect, as they wrongly attributed the lower term to 3s^{2}3d.

TABLE 1

RECOMBINATION COEFFICIENTS, α (10^{-12} cm^3 sec^{-1})

	ELECTRON TEMPERATURE, T_e (° K)		
	100	1000	10000
Ground level	2 8	0 9	0 29
Excited levels	5 7	1 1	0 15
Total	8 5	2 0	0 44

TABLE 2

IONIZATION FUNCTIONS, I (cm^{-3})

	ELECTRON TEMPERATURE, T_e (° K)		
	100	1000	10000
I(Al)	150	640	2900
I(Na)	0.59	2 9	21
I(Na)/I(Al)	0 0039	0 0045	0 0072

According to Figure 1, the cross-section at threshold exceeds that of Na^0 some 150 times—it is not surprising that Al has not been found! Γ is found from equation (2) to be 1.3×10^{-9} sec^{-1}, while the continuum *f*-value is 0.38.

The ground-state recombination rate was calculated from the data of Figure 1. It should be sufficiently accurate to use hydrogenic cross-sections to calculate the rates of recombination onto all other levels except the 3s3p^2. The latter processes, we may assume, do not occur, as they involve two-electron transitions from the 3s^2 ground state of Al$^+$. The hydrogenic recombination rates for $T_e = 100°$ K, 1000° K, and 10000° K were taken from Seaton (1951). It is estimated that this procedure has an uncertainty less than about 30 per cent. The calculated α's are presented in Table 1. The corresponding values of I are given in Table 2, along with those computed for Na by Weigert (1955), using the same radiation field.

III. THE EFFECT OF AUTOIONIZATION

Recently Garton (1950) has confirmed an earlier identification by Selwyn (1928) of a term 3474 cm^{-1} above the ionization limit of the principal series of Al I, as being

$3s3p^2\ ^2S_{1/2}$. This term combines with the ground ^2P term to give a strong doublet, λ 1932/λ 1936, which Garton has observed in absorption. The components of the doublet are about 1 angstrom unit wide, indicating a lifetime of 2×10^{-13} sec for the $^2S_{1/2}$ term. As it is an even term above an ionization limit, it can easily autoionize to the $3s^2\kappa s$ continuum; in all likelihood, this process accounts for the short lifetime of the $^2S_{1/2}$ level, as it would be very rapid. If such autoionization does take place, the ionization rate from the ground level is enhanced by absorption of λ 1932 followed by autoionization. The contribution to Γ will be proportional to f(λ 1932), which is unknown. However, Hudson (1958), in examining the ultraviolet absorption by Ca^0 atoms, found a strong diffuse absorption line at λ 1906, beyond the ionization limit, which he attributed to a process similar to that we are discussing. He found the f-value for this and some weaker lines to total 0.30, compared with the continuum f-value of 0.15. If we take the contribution of the continuum to Γ to be proportional to its f-value, then, in Ca, autoionization increases Γ by a factor of 3. A similar factor in Al would result from an f-value of 0.8 for λ 1932. As such an f-value cannot at present be ruled out, it is possible that the true Γ is as much as three times as great as we have calculated.

Will not α be increased as well by the inverse process? Detailed study based on the Milne relation for radiationless recaptures shows that if captures on the positive energy state (energy E above the limit) are followed by radiative transitions to only the ground state of the atom, the effective recombination rate is

$$\alpha^* = \frac{\varpi_E}{2\varpi_+^1} A_{E0} \left(\frac{h^2}{2\pi m k T_e}\right)^{3/2} e^{-E/kT_e}, \tag{4}$$

where A_{E0} is the spontaneous radiation rate from the level of energy E to the ground state of the atom, and ϖ_E is the statistical weight of the E-level. At temperatures low compared to χ^1/k, one can show that the ratio of this to the radiative recapture rate on the ground state is

$$\frac{\alpha^*}{\alpha_1} = \frac{f_l}{f_c}\left(\frac{\lambda_1}{\lambda_E}\right)^2 \frac{\Delta\nu}{\nu_E - \nu_1}\left(\frac{E}{kT_e} e^{-E/kT_e}\right). \tag{5}$$

Here f_l is the f-value for the line, λ 1932, and f_c that for the continuum, while $\Delta\nu$ is the effective frequency width of the continuum, and λ_1 is the ionization limit (2071 A) and λ_E the line at 1932 A. The expression in parentheses has a maximum value of e^{-1} at $T_e = E/k = 5000°$ K. Hence the upper limit on α^* is $1.18(f_l/f_c)\alpha_1$. At 100°, α^* is negligible, while at 1000° it equals 0.11 $(f_l/f_c)\alpha_1$, and at 10000°, 0.97 $(f_l/f_c)\alpha_1$. The dependence on temperature, of course, reflects the requirement for energetic electrons to excite the $3s3p^2$ level. If we take $f_l/f_c = 2$, as in Ca^0, recaptures through the $3s3p^2$ level are negligible at 100°. However, at 1000° they are 10 per cent of the total listed in Table 1, and at 10000° they are 130 per cent.

In conclusion, then, we see that Γ may be as large as three times the value calculated in Section II. At low temperatures, α is unaffected by autoionization, and I may therefore be three times the values of Table 2. At high temperatures, α is also increased by autoionization to about 2.3 times its original value, with the result that the I of Table 2 is increased only 30 per cent.

IV. EQUIVALENT WIDTHS

χ^2 Ori and ζ Per have the strongest known interstellar sodium lines. We shall therefore use the equivalent widths of λ 3302 measured by Spitzer and Field (1955) to estimate according to equation (1) and Table 2 the equivalent width of λ 3944. The measured values for λ 3302 were 75 mA in χ^2 Ori and 27 mA in ζ Per. We assume that the lines are formed in an H I region, as shown by Spitzer and Field to be likely. We note in passing that Helfer and Tatel (1959) concluded from Strömgren (1948) that sodium

lines are formed mainly in H II regions; it appears to us that, in fact, Strömgren reached precisely the opposite conclusion. If the lines are formed in an H I region, the previous analysis will apply; we may take $T_e = 100°$ K, although it is clear from Table 2 and Section III that our conclusions will be little affected if T_e is as high as 1000°. The predicted equivalent widths are given in Table 3.

An upper limit for W (λ 3944) has recently been obtained in ζ Per by Rogerson, Spitzer, and Bahng (1959). Using a photoelectric spectrophotometer, they were able to show that W (λ 3944) = (-0.4 ± 2.0 m.e.) mA. Perhaps we have here an indication that autoionization is important, although definite conclusions await further observations. It appears, however, that the ideal sensitivity of the instrument used, about 0.2 mA, should be sufficient to detect Al I even if autoionization is present. When and if it is found, only Co^+ and Ni^+ remain to be accounted for in the list of expected interstellar ions.

TABLE 3

PREDICTED EQUIVALENT WIDTHS (MA) FOR λ3944 IN TWO STELLAR SPECTRA

No Autoionization		Reasonable Autoionization*	
χ^2 Ori	ζ Per	χ^2 Ori	ζ Per
7 5	2 7	2 5	0 9

* By "reasonable autoionization" we mean the factor of 3 discussed in Sec. III.

TABLE 4

FINE-STRUCTURE LEVELS OF INTERSTELLAR IONS

Ion	Levels	Excitation Energies (° K)
Al^0 . . .	$^2P_{1/2, 3/2}$	161 2
Ti^+	$^4F_{3/2, 5/2, 7/2, 9/2}$	135 2, 324 .4, 565 7
Fe^0	$^5D_{4, 3, 2, 1, 0}$	598 4, 1012 8, 1277 8, 1407 1
Co^+	$^3F_{4, 3, 2}$	1367 2, 2297 9
Ni^+	$^2F_{5/2, 3/2}$	2168 0

We feel very indebted to Dr. M. J. Seaton for his critical remarks at several stages of the investigation.

APPENDIX

THE POPULATION OF FINE-STRUCTURE LEVELS OF INTERSTELLAR IONS

Various authors have pointed out that lines arising from low-lying excited levels of interstellar ions are not observed and that the probable explanation is that collisions, while often energetic enough, are not rapid enough to maintain the excited populations against radiative de-excitation. Now the $^2P_{3/2}$ level of Al^0 is only 112 cm^{-1} above ground and hence will radiate very slowly; furthermore, the usual collision rates calculated for electron-ion collisions will have to be modified for the neutral atom. It seemed worthwhile, therefore, in connection with the present investigation, to give at least rough quantitative estimates of populations for the various ground-term fine-structure levels occurring in interstellar ions. These levels are listed in Table 4, together with their excitation energies (omitting the ground level) in temperature units. How

splendid it would be if thermodynamic equilibrium obtained for these levels; they would constitute a well-graduated thermometer of kinetic temperatures which could be read by using line ratios! The actual situation, however, is established by statistical equilibrium. For a two-level system we find

$$\frac{N_2}{N_1} = \frac{\varpi_2}{\varpi_1} e^{-E_{21}/kT} (1 + a)^{-1}; \qquad a = \frac{A_{21}}{C_{21}}. \tag{A-1}$$

Here A_{21} is the radiative and C_{21} the collisional de-excitation rate. We shall be content to consider equation (A-1), although, of course, for more than two levels there will be additional terms.

The values of A_{21} for the first excited state in Al^0, Ti^+, and Fe^0 were calculated from the formulae of Pasternack (1940) for magnetic-dipole transitions; they are 3.8×10^{-5} sec $^{-1}$, 1.1×10^{-4} sec^{-1}, and 9.9×10^{-3} sec^{-1}, respectively.

As Ti^+ is positively charged, the cross-section for collision with electrons and subsequent de-excitation is very large. Following Seaton (1955), we have

$$C_{21} = \frac{8.6 \times 10^{-6} \Omega}{\varpi} \frac{N_e}{T_e^{1/2}}, \tag{A-2}$$

where Ω is a dimensionless collision strength, which for ^2P transitions in Si^+ was calculated to be 7.7 (Seaton 1958*b*). Putting it equal to 10 for Ti^+ and taking $N_e = 2 \times 10^{-3}$ cm^{-3} ($N_H = 10$ cm^{-3}), and $T_e = 100°$ K, we find $C_{21} = 2.9 \times 10^{-9}$ sec^{-1}; and hence $a(Ti^+) = 3.8 \times 10^4$. The resulting depopulation of the $^4F_{5/2}$ level is not in disagreement with observation.

TABLE 5

DISPERSION PARAMETERS, c, AND KINETIC CROSS-SECTIONS, σ_K, FOR COLLISIONS WITH H ATOMS AT 100° K

Atom	c	σ_K (10^{-14} cm^2)	Atom	c	σ_K (10^{-14} cm^2)
H	6	0 44	Al	300	1 6
O	8	0 49	Fe	830	2 3

The cross-section corresponding to the above assumption, $\Omega = 10$, is about 3×10^{-13} cm^2. It seems likely that electron collisions with neutral atoms will not exhibit such large cross-sections In this case, however, collisions with H atoms will be effective, owing to the possibility of electron exchange in a close approach. Even supposing that electron collisions *are* as effective for atoms, collisions with H atoms at 100° K will dominate if the cross-section exceeds $43 \times 2 \times 10^{-4} = 8\,6 \times 10^{-3}$ that computed for electron collisions, or about 2.6×10^{-15} cm^2, owing to the large abundance of H atoms. That such cross-sections are not unlikely can be seen from the cross-section for hyperfine de-excitation in H by electron exchange; this is 5.7×10^{-15} cm^2, according to Purcell and Field (1956).

The latter authors write

$$\sigma_{21} = P_{21} \sigma_K , \tag{A-3}$$

where σ_K is the kinetic cross-section for atom-H collisions and P_{21} is the probability of de-excitation per collision. We can calculate σ_K by using the arguments of Purcell and Field if the interatomic force law is known. If we assume that the latter is a dispersion force, we find

$$\sigma_K = 50 \pi a_0^2 \left(\frac{c}{c_H}\right)^{1/3} \left(\frac{T_K}{100}\right)^{-1/3}, \tag{A-4}$$

where the dispersion parameter c is proportional to the atomic polarizabilities and can be estimated from equations (13.2–18*b*), (13.3–28), and (13.2–25) of Hirschfelder, Curtiss, and Bird (1954). The values of c and σ_K (100° K) thus estimated are given in Table 5.

The exact value of c_H is known to be 6.5, and the σ_K(H) calculated by Purcell and Field, including small terms in the interatomic force, is 0.57×10^{-14} cm^2. The values of Table 5 can

therefore be expected to be accurate enough for our present purposes It should be noted that the rather large σ_K's are the result of trapping by the interatomic forces at large distances, owing to the low kinetic energies of the atoms.

The value of P_{21} can in principle be found from a detailed consideration of electron angular momentum states before and after the collision. In this way Purcell and Field showed that it is $\frac{1}{3}$ for hyperfine de-excitation. We have not yet carried out such a procedure for the present problem and shall therefore put $P_{21} = 1$, realizing that this estimate may be too large by a factor of 10. It may be noted that P_{21} comes out formally to be 1 1 for $P_{3/2} \rightarrow P_{1/2}$ transitions in Na^0 stimulated by collisions with argon atoms (Lochte-Holtgreven 1928).

In accordance with the above assumptions, $C_{21} = N_H(8kT_K/\pi M_H)^{1/2}\,\sigma_K$, and with $N_H = 10\ cm^{-3}$, $T_K = 100°$ K, this gives $C_{21} = 7.2 \times 10^{-9}\ sec^{-1}$, $2.4 \times 10^{-8}\ sec^{-1}$, and $3.4 \times 10^{-8}\ sec^{-1}$ for O^0, Al^0, and Fe^0, respectively—all considerably larger than the electron collision rate for Ti^+. Thus α comes out to be 1.6×10^3 for Al^0 and 2.9×10^5 for Fe^0. Therefore the iron levels will be heavily depopulated (in accordance with observation), and Al atoms will be mostly in the $^2P_{1/2}$ level, as stated in the text.

Two further applications of these ideas may be mentioned. First, it appears that the cooling of the interstellar gas by O–H collisions may not be negligible. We find an energy loss per electron (for comparison with electron-ion cooling) per unit H-atom density,

$$\mathfrak{L}_{HO} = 3.6 \times 10^{-24} P_{21} T_K^{1/2}\, e^{-227/T_K} \text{erg}^{-1}\ \text{sec}^{-1}, \qquad \text{(A-5)}$$

a value which exceeds electron-ion cooling (Seaton 1955) by a factor of $13P_{21}$ at 100° K. An accurate evaluation of P_{21} is evidently desirable. Professor Lyman Spitzer, Jr., has kindly pointed out that Bates (1951) considered the same process for the cooling of the upper atmosphere. However, Bates does not estimate P_{21} beyond saying that it likely exceeds 10^{-4}, a critical value in his theory.

Finally, we have considered the circumstellar lines in α Her observed by Deutsch (1956) He finds λ 3962 arising from the $^2P_{3/2}$ level of Al^0 in absorption in the M-giant spectrum, while only ground-level iron lines were seen. Deutsch's model, based on clouds having $T = 2500°$ K, $N_e = 10^6\ cm^{-3}$, and $N_H = 10^{10}\ cm^{-3}$, seems to be inconsistent with the ideas developed above, since $\alpha(Fe^0)$ would be about 10^{-3} and $(\varpi_2/\varpi_1)e^{-E/kT}$ would be 0.62 for the excitation of the $^5D_3$ level of iron, so that a line from that level should be observed In addition, if the density is as high as Deutsch assumed, the Al^0 levels would be Boltzmann-populated; the ratio of λ 3962 to λ 3944 would then reflect the kinetic temperature The observed ratio indicates a value nearer 100° K than the 2500° K taken by Deutsch. Thus one may explain the data with Deutsch's densities and a much lower temperature or by his temperature with much lower densities. If one adopts the latter approach, a density of about $3 \times 10^4\ cm^{-3}$ is indicated by the Al^0 line ratio; such a low density would also account for the absence of lines from excited levels of Fe^0. While the foregoing interpretations are only rough, they show the kind of information that can be gleaned from observation of fine-structure levels in interstellar space.

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