N 70 25322
NASA CR109488

ULTRAVIOLET ABSORPTION LINES IN COSMIC RAY HEATED H I REGIONS

by

Joseph Silk
Princeton University Observatory

January 1970

SUMMARY

A small but significant fraction of the more abundant atoms in H I regions will be ionized by low energy cosmic rays, if such particles are indeed responsible for heating and ionizing the neutral hydrogen. Some of the higher ion states in H I regions should be detectable by rocket or satellite spectroscopic observations of the ultimate absorption lines. Equivalent widths of order 100 mA are obtained for ions such as C III, N II, N III, Si III and S III in low density H I regions.

Observations of the interstellar medium, primarily by the 21 cm line of neutral hydrogen and the dispersion measures of pulsars, indicate that the mean temperature and electron density in H I regions are too high to be explained without invoking a nonthermal energy source such as subcosmic rays (Hayakawa, Nishimura and Takaynagi 1961; Pikelner 1968; Spitzer and Tomasko 1968; Field, Goldsmith and Habing 1969) or soft x-rays (Silk and Werner 1969; Sunyaev 1969).

The heating and ionization of H I regions by energetic particles has in fact been investigated in considerable detail (Spitzer and Scott 1969; Goldsmith, Habing and Field 1969). However no attention has been given to the effect of energetic particles on the ionization equilibria of the heavier atoms present in H I regions. With the advent of space satellite ultraviolet spectroscopy in the near future, many of these atoms should produce observable absorption lines. Spitzer and Zabriskie (1959) have listed the absorption lines formed in the most abundant states of interstellar atoms.

In the present note, I wish to point out that a small but significant fraction of the more abundant atoms in H I regions will be present in higher states of ionization, owing to the effects of energetic particles, and will give rise to detectable absorption lines. These ion states are listed in Table I. In order to calculate the ionization equilibria, the results of the classical theory have been used for the cross-section for electron impact ionization, Q_i. The cross-sections for ionization by proton and electron impact are approximately equal at the same velocity, provided that the proton energy E exceeds about 0.2 MeV. For the ionization of an ion with ionization potential I and number of electrons ζ_i in the outer shell, a reduced cross-section may be defined by

$$\sigma_i = \frac{1}{\zeta_i}\left(\frac{I}{I_H}\right)^2 Q_i \quad ,$$

where I_H is the hydrogen ionization potential, 13.6 eV. If $\epsilon = m_e E/m_p I$, then approximate classical theories indicate that $\sigma_i(\epsilon)$ should be a universal function, the same for all elements in all stages of ionization. More refined calculations show that σ_i does in fact differ appreciably for different elements; however a mean σ_i may be defined which is consistent with all of the results to within a factor of about 2 (Seaton 1964).

Only radiative recombinations are considered, and it is assumed that the recombinations are hydrogenic. Hence the recombination coefficient to the i^{th} state of ionization of an atom is

$$\alpha_i = (i + 1)^2 \alpha_H ,$$

where α_H is the total recombination coefficient for hydrogen. One then obtains the general result for the abundance of the (i + 1)th state of an ion X,

$$\frac{N(X^{i+1})}{N(X^i)} = \frac{y\zeta_i}{(i+1)^2} \frac{I_H}{I} ,$$

where $y = n_e/n_H$.

The relative abundances of the more abundant ions which have transitions from the ground state at wavelengths longward of 912 Å are listed in column 2 of Table 1, normalized to 10^6 for hydrogen. In column 3, the corresponding wavelengths are listed. In cases where there are several lines, only that line has been selected with the largest oscillator strength f; other transitions of interest are indicated in parentheses. The corresponding f-values are listed in column 4, and are taken from a recent compilation by Smith (1969). Columns 5 and 6 contain the optical depths τ_0 at the center of each line, and the corresponding equivalent widths for two model H I regions. The curve of growth tabulated by Spitzer (1968) has been used. Case (a) represents a "standard" cloud (Spitzer 1968) of density $n_H = 10$ cm^{-3} and size 7 pc. A mean electron density $n_e = 3 \times 10^{-3}$ (Spitzer and Scott 1969), and a radial velocity dispersion of 2 km/sec have been assumed. For case (b) the parameters $n_H = 0.1$ cm^{-3} and $n_e = 2 \times 10^{-2}$ cm^{-3} are chosen to represent the intercloud medium (Field, Goldsmith and Habing 1969). A line of sight is considered which traverses 100 pc of this low density medium, and a dispersion in radial velocities is adopted of 8 km/sec along the line of sight.

Because the absorption lines in the dominant states of the more abundant ions such as C II, N I, Al II, Si II and S II are heavily saturated (cf. Spitzer and Zabriskie 1959), Table 1 indicates that the absorption lines produced in H I regions by C III, N II, Al III, Si III and S III should be easily detectable with an ultraviolet spectrograph in space, with resolution comparable to that of ground-based instruments. Even the ions C IV, N III and S IV should be observable for H I regions with density $n_H \lesssim 1$ cm^{-3}, although the line strengths depend on y^2, and so will be a sensitive indicator of the degree of ionization of the H I region. The present calculation indicates that even though H I "standard" clouds produce strong absorption lines for the most abundant ion states, the low density, more highly ionized H I regions tend to produce even broader features, because the lines are less heavily saturated. Low density H I regions dominate completely for those lines produced by the higher ion states.

Similar absorption lines for the higher ion states are, of course, predicted in H II regions where these same ions are collisionally ionized by thermal electrons. However it should be possible to distinguish between those lines formed in H I and H II regions from the Doppler shifts measured for individual lines because the lines characteristic of H I regions such as C II, O I and N I will not be produced in H II regions. Comparison with the radial velocities of known H I or H II regions along the line of sight should also enable some separation to be made. It would be feasible to determine whether the intercloud medium is predominantly hot H I or low density H II by choosing a star at sufficiently high galactic latitude so that the line of sight did not pass through any dense H I regions. The failure to detect any of these lines in the interstellar medium would pose grave difficulties for the hypothesis that H I regions are heated by energetic particles. Analogous predictions of absorption line intensities may be made for H I regions heated by soft x-rays; these will be presented in a subsequent paper.

I wish to acknowledge helpful conversations with Drs. W. H. Smith and L. Spitzer. This research has been supported in part by National Aeronautics and Space Administration grant NGL-31-001-007 to Princeton University.

TABLE I

ION ABUNDANCES AND EQUIVALENT WIDTHS
OF INTERSTELLAR LINES

Ion	Abundance relative to $H = 10^6$	Wavelength* (A)	f_{abs}	τ_0 (a)	τ_0 (b)	Equivalent Width (mA) (a)	Equivalent Width (mA) (b)
C II	300	1334.5 (1036.3)	0.113	4800	180	73	232
C III	130 y	977	0.28	12	28	31	144
C IV	8 y	1548.2 (1550.8)	0.19	0.002	0.4	0.06	9.1
N I	90	1199.6 [3] (1135 [3], 964 [3])	0.14	1600	60	62	194
N II	430 y	1084 (915.6)	0.11	16	40	35	161
N III	200 y^2	989.8	0.1	0.02	3.1	0.3	89
Al II	1.9	1670.8	1.8	605	22	81	237
Al III	0.7 y	1854.7 (1862.8)	0.6	0.002	0.6	0.06	61
Si II	30	1260.4 (1808, 1526.7 1304.4, 1193.3)	0.68	2700	102	67	215
Si III	18 y	1206.5 (1895.5)	1.43	10.3	26	38	173
Si IV	1.7 y^2	1393.7 (1402.7)	0.55	0.001	0.2	0.02	17
S II	17	1259.5 (1253.8, 1250.5)	0.012	27	0.1	46	52
S III	12 y	1190.2 (1012.5)	0.48	2.2	5	23	126
S IV	2 y^2	1062.7	0.59	0.01	0.2	0.2	13
A I	4.2	1048.2 (1066.7)	0.23	108	4	4	105
A II	29 y	919.8	0.009	0.08	0.2	1	11

*Whenever several ultimate lines appear in a multiplet, with mutual separation 1 A or less, only the largest wavelength is given, with the number of lines in the multiplet indicated in square parentheses.

REFERENCES

Field, G. B., Goldsmith, D. W. and Habing, H. J. 1969, Ap. J. (Letters), **155**, L149.

Goldsmith, D. W., Habing, H. J. and Field, G. B. 1969, Ap. J., **158**, 173.

Hayakawa, S., Nishimura, S. and Takaynagi, K. 1961, Pub. Astr. Soc. Japan, **13**, 184.

Pikelner, S. 1968, Soviet Astr.-A. J., **11**, 737.

Seaton, M. J. 1964, Planet. Space Sci., **12**, 55.

Silk, J. and Werner, M. W. 1969, Ap. J., **158**, 185.

Smith, W. H. 1969 (private communication).

Spitzer, L. 1968, Diffuse Matter in Space (New York: Interscience).

Spitzer, L. and Scott, E. H. 1969, Ap. J., **158**, 161.

Spitzer, L. and Tomasko, M. G. 1968, Ap. J., **152**, 971.

Spitzer, L. and Zabriskie, F. 1959, P. A. S. P., **71**, 412.

Sunyaev, R. 1969, Astron. Zh., **46**, 929.