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P. M. Gondhalekar and R. Wilson

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The interstellar ionization balance due to ultraviolet radiation

By P. M. Gondhalekar
Appleton Laboratory, Culham Laboratory, Abingdon, Oxfordshire

and R. Wilson
University College London, Gower Street, London, W.C. 1

A new estimate of the interstellar ultraviolet radiation field is used to analyse some well established observations of interstellar Na I, Ca II, Mg I, II in ζ, ε and δ Ori. Four models of the interstellar medium are used and chemical abundances derived relative to that of hydrogen, obtained from Lyman α data. The scatter of the results is discussed together with the apparent anomalous abundance of calcium.

Introduction

The ionization balance of those species in the interstellar medium whose ionization potential is lower than that of atomic hydrogen will be caused predominantly by the local ultraviolet radiation field. This is produced by the net contributions of early type stars in the galaxy (the diffuse radiation field) and is perturbed in the neighbourhood of hot stars which are generally used as the background sources for studying interstellar effects. Early estimates of the interstellar ionization balance were hampered by the gross uncertainties of the ultraviolet nature of stellar spectra or interstellar extinction. As this situation was improved by observations so did the estimates of the ultraviolet radiation field as carried out by Habing (1968) and then by Witt & Johnson (1973). More recently a calculation has been carried out by Gondhalekar & Wilson (1974) and one of the purposes of this paper is to apply this new estimate of the diffuse ultraviolet radiation field to the analysis of some well established observations. At the same time, a number of models of the interstellar medium have been considered so as to determine their effect on the derivation of physical and chemical parameters. The observations selected are of the stars ζ, ε and δ Ori, and the lines considered are the resonance lines of Na I, Ca II and Mg I, II. The ionization balance of these elements is considered as imposed by the diffuse ultraviolet field plus that due to the background stars. Four models of the distribution of material in the interstellar space have been considered and the abundances of sodium, calcium and magnesium have been computed in each case.

Diffuse ultraviolet radiation

The diffuse ultraviolet radiation field in interstellar space has been recently calculated (Gondhalekar & Wilson 1974) from a galactic model but using, as far as possible, observational data for stellar ultraviolet emissions, interstellar extinction in the ultraviolet and the albedo of the grains. The result is reproduced in figure 1. Between 1400 and 2750 Å it was calculated by using observations of unreddened stars made by the S2/68 experiment on the Esro satellite TD1A (Boksenberg *et al.* 1973). Between 912–1400 Å the stellar emissions were obtained from the line blanketed model atmospheres of van Citters & Morton (1970) and Bradley &

Morton (1969), the fluxes being scaled to agree with the observations in the 1400–1700 Å region. Interstellar data for extinction were taken from Bless & Savage (1972) and Boksenberg *et al.* (1973), and for albedo from Witt & Lillie (1973). The strong absorption by lines of the Lyman series of neutral hydrogen in interstellar space has also been included.

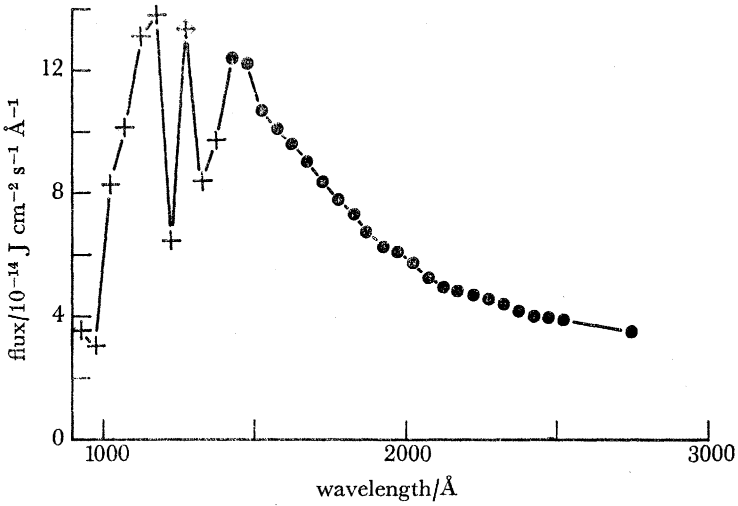

FIGURE 1. Average interstellar radiation field in the ultraviolet as calculated by Gondhalekar & Wilson (1974).

IONIZATION EQUILIBRIUM

For atoms whose ionization threshold lies below that of hydrogen, the ionization equilibrium in interstellar space is determined by a balance between photoionization by the local ultraviolet radiation field and radiative recombination, i.e.

$$\frac{n_{i+1}n_e}{n_i} = \frac{\Gamma}{\alpha}. \qquad (1)$$

Where n_i, n_{i+1} (cm^{-3}) are the number densities in the i, $(i+1)$ stages of ionization for the element under consideration, n_e (cm^{-3}) is the electron number density, Γ (s^{-1}) is the photoionization rate coefficient, and α (cm^3 s^{-1}) is the radiative recombination rate coefficient. Since the population of each species is effectively concentrated in the ground state, Γ is given by

$$\Gamma = 10^{-8}\,(hc)^{-1}\int_{\lambda_L}^{\lambda_0} a_\lambda \lambda F_\lambda \,\mathrm{d}\lambda, \qquad (2)$$

where a_λ (cm^{-2}) is the photoionization cross-section at wavelength λ (Å), and F_λ (J cm^{-2} s^{-1} Å^{-1}) is the local radiation flux. The integration is carried out between the ionization limit λ_0 of the ion under consideration and the Lyman limit λ_L of atomic hydrogen beyond which the radiation field is negligible. The photoionization rates for Na, Ca and Mg were calculated for the combined effect of the diffuse field (figure 1) and the emission from the bright background stars which was derived in a similar fashion to the former. Laboratory measurements were used for the photoionization cross-sections of Na I (Hudson & Carter 1967), Ca I (Carter, Hudson & Breig 1971) and Mg I (Ditchburn & Marr 1953) together with a computed value for Ca II (Black, Weisheit & Laviana 1972). The recombination coefficients were taken from the calculations of Seaton (1951) and Tarter (1971).

Observational data

For the selected stars ζ, ε and δ Ori, the interferometric observations of Hobbs (1969) and Marschall & Hobbs (1972) were adopted for the Na I D lines and the Ca II K line. The equivalent widths of resolved components were measured and column densities derived by constructing curves of growth in the manner described by Hobbs (1969). For Mg I and Mg II, the column densities to the Orion stars were taken directly from Boksenberg *et al.* (1972), who derived them

	model I			model II			model III			model IV		
$10^{-3}\,n_{e,c}/\mathrm{cm^{-3}}$	1.36	1.03	1.89	1.36	1.03	1.89	1.36	1.03	1.89	1.36	1.03	1.89
$10^{-3}\,n_{e,i}/\mathrm{cm^{-3}}$				0.01	0.01	0.02	0.01	0.01	0.02	0.91	0.73	1.26
$10^{-1}\,n_{H,c}/\mathrm{cm^{-3}}$				10.0	10.0	10.0	10.0	10.0	10.0	2.10	1.70	2.91
$10^{-2}\,n_{H,i}/\mathrm{cm^{-3}}$							1.0	1.0	1.0	2.50	2.30	3.5
cloud size/pc				8.45	7.25	10.10	7.05	6.05	8.30	33.4	39.8	27.2

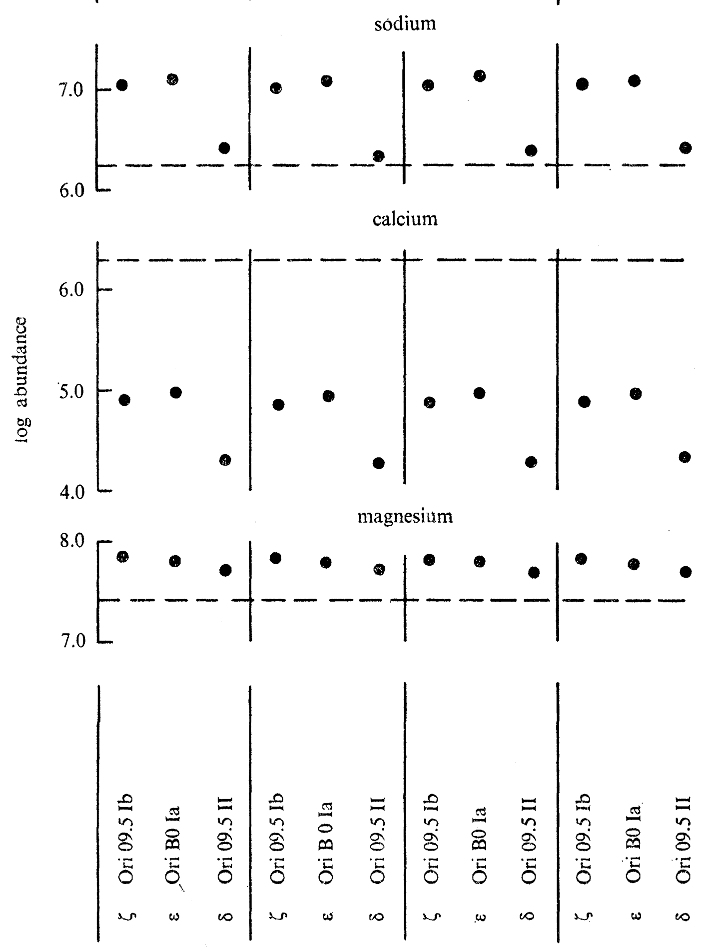

Figure 2. Physical parameters derived from observations of ζ, ε and δ Ori for four models of the interstellar medium together with derived chemical abundances.

from their ultraviolet balloon observations of the appropriate resonance lines. In addition to these data, the following analysis uses the column densities of atomic hydrogen derived by Bless & Savage (1972) from OAO-2 observations of interstellar Lyman α.

Interstellar models

The analysis has been carried out for four models of the interstellar medium in the direction of Orion. In the first (model I of figure 2) the gas is assumed to be uniformly distributed between the background stars and the Sun. The remaining three models are based on a number of clouds which are assumed to be uniformly distributed along the line-of-sight and 100 pc or more from the background stars. The number of clouds were adopted on the basis of the observations (Hobbs 1969) giving 5, 6 and 4 respectively for ζ, ε and δ Ori. In the first of these multicloud models (model II in figure 2) the interstellar material is concentrated entirely in the clouds for which a hydrogen density of 1 cm^{-3} and a kinetic temperature of 60 K is assumed. The sizes of the clouds were then obtained from the observed column densities of neutral hydrogen. In model III the temperature and density in the clouds were taken to be the same as for model II but an intercloud medium was introduced with a hydrogen density of 0.01 cm^{-3} and a kinetic temperature of 460 K. In this case the dimensions of the clouds were somewhat less than in model II in order to reproduce the observed hydrogen column densities.

The last multicloud model considered is based on the physical approach of Field, Goldsmith & Habing (1969) and Hjellming, Gordon & Gordon (1969), who considered the heating of the interstellar medium by energetic particles and showed that the interstellar gas can be distributed into two coexisting phases in pressure equilibrium; a cool, dense phase (cloud) and a hot, tenuous phase (intercloud medium). The cool and the hot phases of interstellar medium also result if the interstellar medium was heated by hard ultraviolet radiation (Bergeson & Souffrin 1971). The particular pressure equilibrium model adopted is from Hjellming *et al.* (1969) and has cloud and intercloud temperatures of 60 K and 460 K rsepectively. These temperatures were adopted in the previous two models for uniformity. Since the pressure equilibrium model gives electron and hydrogen density ratios for cloud–intercloud regions, the determination of one density allows the model to be fully specified. Such a density (electron) can be determined from the ionization balance equation (1) with the column densities of Mg I and Mg II and, hence, in this case, unlike models II and III where cloud and intercloud densities had to be assumed, a full solution to the problem is possible.

Results

The results of the analysis are displayed in figure 2 for the three stars and four models; subscripts c and i are used to identify cloud and intercloud values of electron and hydrogen densities. The electron densities are derived by substituting the observed column densities of Mg I and Mg II in the ionization balance equation (1). This gives values appropriate to the clouds since the lines observed are essentially produced there. The cloud electron densities are therefore independent of the model but show some variation from star to star. The intercloud values of electron density are given in figure 2 for the two relevant models (III and IV). In the former case, the values are a direct result of the assumed intercloud density and the assumption of a uniform ionization level; in the latter case, they are a derivation of the physical model. The hydrogen densities for cloud and intercloud media are also given for those models for which they are appropriate. With the exception of model IV, these are assumed values. In the last row of the tabular part of figure 2 are listed the average cloud sizes required to match the observed column densities of neutral hydrogen.

Using the above physical parameters, the total abundance of each element in the line of sight can be calculated for each star on the basis of each model. The results are displayed graphically in figure 2 where the logarithm of the sodium, calcium and magnesium abundances are plotted on the normal scale of lg (H) = 12.

It is noteworthy that the values for magnesium vary little from star to star or model to model. This is due to the fact that this element is observed in its most populated state (Mg II). Consequently, the derived chemical abundance is largely insensitive to the physical assumptions made. This is also true of the hydrogen abundances to which the other elements are normalized but it is not true of sodium and calcium. Both of these elements are observed in a weakly populated state (Na I and Ca II respectively) and therefore depend heavily on the physical assumptions which lead to an estimate of their ionization equilibria. This probably explains the much larger scatter in the estimates of the abundance of these elements. The variation from star to star is of the same order as from model to model and the dispersion in abundance estimates, expressed as a standard deviation, is ± 0.4 dex. This gives some indication of the uncertainty in deriving interstellar chemical abundances of elements like sodium and calcium.

Also shown in figure 2 are the normal cosmic abundances of the elements concerned as listed by Allen (1973). If we compare these with the average value for the three stars derived for the most realistic model (IV) then the magnesium abundance is a factor *ca.* 2.4 higher than the normal cosmic value and sodium a factor of *ca.* 3. Considering the uncertainties involved, the abundances of these two elements can be taken as normal. This is not the situation with the remaining element, calcium, which is a factor of *ca.* 40 underabundant with respect to the normal cosmic value. This deficiency in interstellar calcium has already been noticed by Herbig (1968) and Habing (1969) and confirmed more recently by Pottasch (1972). The present value is considerably higher ($\times 20$) than that derived by Pottasch but still leaves an underabundant factor of *ca.* 40.

The calcium abundance is derived from the column density of Ca II, the ionization potential of which (11.9 eV) lies closer to that of hydrogen (13.6 eV) than the other elements considered here. Its ionization level therefore depends on the intensity of the local radiation field just below the Lyman limit where the estimate is most inaccurate. Some caution, therefore, should be exercised and better estimates of the radiation field (and, perhaps, the photoionization cross-section) should be sought before accepting the interstellar calcium abundance as anomalous.

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