A Study of Interstellar Lines in the Rocket Spectrum of δ Scorpii

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A study of interstellar lines in the rocket spectrum of δ Scorpii

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An analysis is made of ten interstellar lines in the vacuum ultraviolet spectrum of δ Sco. The data were taken from a rocket spectrogram with wavelength coverage extending from 1177 to 1717 Å with a resolution of approximately 0.15 Å. Column densities of C^0, C^+, N^0, 0^0, Al^+, Si^+ and Fe^+ are derived, from which abundances relative to atomic hydrogen are determined. Compared to corresponding solar abundances, silicon and iron are slightly overabundant whereas the remaining species are underabundant by factors of 1.8 to 8.6. It is shown that the relative Fe abundance may be made significantly less than the solar value by arbitrarily increasing the velocity dispersion of the Fe^+ ions by a factor of 2. The relative populations of the carbon atoms ground state fine structure levels combined with two possible mean cloud temperatures of 47 and 76 K determined from the interstellar H_2 spectrum yield a mean cloud density of 250 and 150 cm^{-3} respectively. Using the appropriate column densities of neutral and singly ionized carbon atoms, the average ratio of the electron density at the hydrogen atom density for each temperature is found to be 2.1×10^{-4} and 4.8×10^{-4} respectively.

1. Introduction

Since 1970, rocket and satellite measurements of vacuum ultraviolet interstellar lines have uncovered much information about the interstellar medium. As expected, the resonance lines of molecules, atoms and singly ionized atoms are sensitive indicators of the physical conditions prevailing in the interstellar clouds as well as the interaction of the gas with the radiation field and dust particles. In this paper, I should like to report the results of a rocket observation of the star δ Sco in which two, high resolution spectrograms were recorded. One of these contained the interstellar spectra of C I, C II, N I, O I, Si II, Al II and Fe II from which it was possible to derive column densities of the respective atoms and ions. These results together with estimates of the mean cloud temperature were used to deduce values of the mean hydrogen atom and electron densities in the clouds intersected by the line of sight.

2. Data analysis

As an example of the interstellar line spectra, I have shown in figure 1*a* the reduced data for a C I triplet near 1561 Å. The plate scale is about 4.5 Å mm^{-1}, and at this wavelength the resolution is 0.15 Å. Transitions from the three fine structure levels of the ground state configuration are resolved, a circumstance which makes possible an estimate of the mean cloud density.

Unfortunately, it was not possible to find a sufficient number of suitable lines for any detected atom or ion by which the Doppler widths could be determined by fitting the line equivalent widths to a curve of growth. Consequently, it was necessary to construct a simple model of the velocity distribution of matter in the line of sight. In order to do this, recourse was made to the work of Marschall & Hobbs (1972) who obtained very high resolution spectra of the interstellar Ca II K-line using a Fabry–Perot interferometer. In the case of δ Sco two cloud components were resolved with a relative velocity of 3.3 km s^{-1}. The lines corresponding to each cloud are unsaturated and show that the relative number of Ca^+ ions in each cloud is about 2:1. The larger cloud is characterized by a Doppler width of 1.55 km s^{-1} whereas the Doppler width of the smaller cloud is 2.16 km s^{-1} or somewhat larger. Curves of growth for each line of interest were calculated under the assumptions that the spatial and velocity distribution of all the interstellar atoms and ions detected in this observation are identical to those of the Ca^+ ions and that the velocity distributions are Maxwellian. Since contributions to the ultraviolet line from each cloud component could not be resolved, equivalent widths were computed for the blends arising from absorption in each cloud as well as from unresolvable transitions. Oscillator strengths and Einstein A coefficients compiled by Morton & Smith (1973) were used in the calculations except in the case of the Fe II line where several relevant oscillator strengths were kindly provided to me by R. L. Kurucz. Using the computed curves of growth and measured equivalent widths, column densities of interstellar C^0, C^+ N^0, O^0, Al^+, Si^+ and Fe^+ were determined.

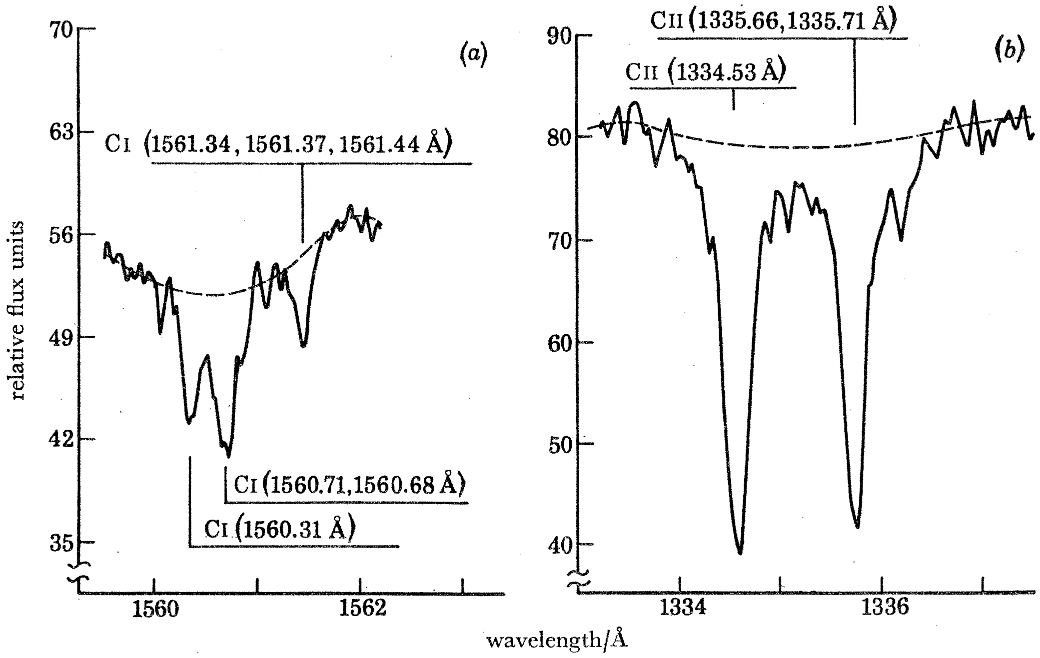

FIGURE 1. Segments of the δ Sco spectrum containing various interstellar lines. Dashed lines indicate the assumed background stellar flux.

In order to compare the column densities of the ions with the hydrogen atom column density (Smith 1973) it is necessary to make a correction for those ions which are located inside an H II region surrounding δ Sco. Based on Palomar Sky Survey prints the H II region was assumed to extend toward the Sun 4.7 pc. An electron density of 2.6 cm^{-3} is adopted on the basis of an Hα emission measure determined by R. J. Reynolds & F. Scherb, again using Fabry–Perot techniques. Details of the calculations may be found in Smith (1972) where H II region column densities were estimated for the case of ζ Oph. This reference includes additional input data which was used in the present calculation. The galactic radiation field, however, was that of

Witt & Johnson (1973), and some of the recombination coefficients were computed using the parametric formulae of Aldrovandi & Péquinot (1972).

One further correction to the C^+ ion column density must be made. This is necessitated by the observation that the C II (1335.7 Å) line is strong, meaning that the elevated $^2P_{\frac{3}{2}}$ fine structure level is populated nearly as much as the ground state $^2P_{\frac{1}{2}}$ level. The spectrum of the C II doublet is shown in figure 1*b*. Under the reasonable assumption that the population of the $\frac{3}{2}$ level occurs inside the H II region but outside the rotating part of the stellar atmosphere, in a shell perhaps, one can estimate the column density of these 'interior' C^+ ions in the $^2P_{\frac{1}{2}}$ level by assuming that the relative population of the fine structure levels is given by the ratio of the statistical weights. This amounts to assuming that the electron density, n(e), in the vicinity of the interior C^+ ions is greater than 1000 cm^{-3}.

When the various subtractive corrections have been made the C^+, Al^+, Si^+ and Fe^+ ion densities are reduced from the uncorrected values by 27, 18, 1.5 and 0.8 % respectively.

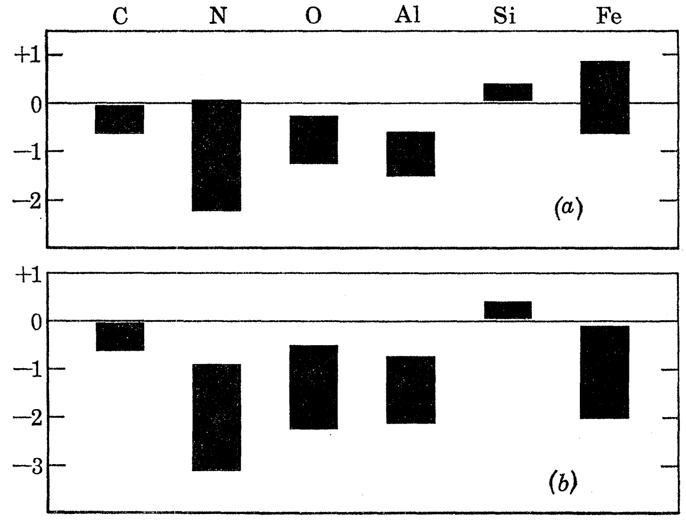

FIGURE 2. Interstellar cloud abundances relative to hydrogen compared to similar relative solar abundances. The length of the bars indicates the magnitude of the uncertainties. The abundances shown in figure 2*b* result when the Doppler widths associated with figure 2*a* are arbitrarily multiplied by a factor of 2.

3. RESULTS

The results are shown in bar graph form in figure 2*a*. The observed abundances relative to hydrogen are compared to solar abundances normalized in the same way via the quantity $\lg\,(A/H)_{obs} - \lg\,(A/H)_{\odot}$. Here, $(A/H)_{obs}$ is the ratio of the observed corrected column density of element A to the observed hydrogen atom column density (Smith 1973), and $(A/H)_{\odot}$ is the solar relative abundance of element A. The length of the bars indicate the uncertainties of the measurements with the predominant contribution arising from the difficulty in locating the background continuum. All the observed lines are formed on the damping part of the curve of growth with the exception of the N I (1200.71 Å) line and the C I (1560.31 Å) line shown in figure 1*a*. The former is located between the saturated and damping parts of the curve of growth which accounts for the comparatively large uncertainty in the N^0 atom relative abundance. The C I (1560.7 Å) and C I (1561.4 Å) lines are formed on the linear part of the curve of growth whereas the C I (1560.31 Å) line is formed between the linear and saturated parts of the curve of growth. Uncertainties in the C^0 atom abundance, however, are unimportant in this context since the C^+ ions are on the order of 3×10^3 times more abundant. The total uncertainty also includes the effect of a 15 % error in deriving the Doppler widths from the Ca^+ K-line data which translates into a typical abundance uncertainty of ± 6 % except in the case of N^0 atoms where the abundance uncertainty is ± 59 %.

4. Discussion

As can be readily seen in figure 2 the species C, N, O and Al are depleted compared to solar abundances by factors running in the mean between 1.8 for carbon to 8.6 for aluminium. This behaviour is to be expected on the basis of previously published Copernicus results (Morton *et al.* 1973), and is commonly attributed to the adsorption of these gas components onto grain surfaces (Spitzer 1968*a*; Field, Goldsmith & Habing 1969). The surprising result is that the silicon and iron abundances are so large; they are comparable to the solar values or perhaps slightly greater. A possible explanation lies in the initial assumption that the velocity distributions of the atoms and ions detected in the vacuum ultraviolet spectrum are the same as that of the Ca^+ ions observed in the K-lines. With the exception of the C^0 atoms, the gas constituents revealed by the rocket observation all represent the dominant ionic state of interstellar clouds, whereas in the same environment, Ca^{2+} ions should be far more abundant than Ca^+ ions. Hobbs (1974) derives a least-squares straight line fit to data from 28 stars which yields the relation $\lg N(Ca^+) \propto (1.5 \pm 0.6) \lg N(H)$, where $N(Ca^+)$ and $N(H)$ are the column densities of Ca^+ ions and H atoms, including those incorporated into H molecules, respectively. In view of this empirical relation, it may be that the denser, and possibly cooler, less turbulent regions of a cloud make a stronger contribution to the overall velocity distribution of the Ca^+ ions than to the overall velocity distribution of the dominant atoms and ions with abundances proportional to $N(H)$ (E. B. Jenkins 1974, private communication).

To examine the consequences of this idea, I have arbitrarily multiplied the Doppler widths corresponding to each cloud component by a factor of 2. When the analysis is repeated making the various corrections to the column densities discussed above, the results are as shown in figure 2*b*. The increase in the velocity dispersion has produced a dramatic change in the derived relative abundance of Fe which becomes less than the solar value; the Fe II (1608.5 Å) line now lies on the saturated part of the curve of growth. A similar reduction in the relative abundances of N, O and Al occurs to a lesser degree. The relative abundances of C and Si, however, are not noticeably affected by the increase in velocity dispersion since these lines are still on the pure damping part of the curve of growth. The accurate determination of the velocity distributions of each interstellar atom or ion is obviously of critical importance.

As pointed out in §2, the resolution of the C I (1561 Å) triplet permits an estimation of the mean cloud density if the cloud temperature is known. A measurement of this latter quantity was made by myself (Smith 1973) using a rather noisy interstellar H_2 spectrum obtained in the same rocket flight which produced the data analysed here. Since the publication of that spectrum is has been shown by Dalgarno, Black & Weisheit (1973) that the temperature determined from the relative population of the $J = 1$ and $J = 0$ rotational levels of the electronic and vibrational ground states assuming a Boltzman distribution is the gas kinetic temperature. In order to minimize the effects of noise, an average temperature of 47 K was found from lines associated with the $v' = 2, 3, 4, 7$ and 8 Lyman bands, some of which are known to coincide with stellar lines. If, however, the temperatures derived from the Lyman, $v' = 4$ band (66 K) and the Werner, $v' = 0$ band (86 K), for which there is little or no stellar line interference, are averaged the resulting temperature is 76 K. This value is in quite close agreement with the Spitzer & Cochran (1973) mean value of 81° (s.d. 13°). Since it was found that only 4.4 % of the line of sight hydrogen atoms were bound into H_2 molecules collisional excitation and de-excitation were assumed to be exclusively due to hydrogen atoms and the collisional rates were calculated using the formulae of Bahcall & Wolf (1968). Only the two excited fine structure levels were used because the lines corresponding to transitions from these levels were unsaturated. The results are that for $T = 76$ K the hydrogen atom density, $n(\mathrm{H})$, is 150, +140, −110 cm^{-3}, and for $T = 47$ K, $n(\mathrm{H}) = 250$, +330, −140 cm^{-3}. Thus, the mean density of the δ Sco clouds seems to be less than the density of the large component of the ζ Oph clouds but approximately a factor of 20 larger than the standard cloud ($n(\mathrm{H}) = 10\ \mathrm{cm}^{-2}$) of Spitzer (1968*b*).

Finally, it is possible to estimate the mean value of $n(\mathrm{e})/n(\mathrm{H})$ in the clouds. This can be accomplished by obtaining the ratio of the corrected column density of C^+ ions, $N'(\mathrm{C}^+)$, to the measured column density of C^0 atoms, $N(\mathrm{C}^0)$, and assuming that the gas is in ionization equilibrium. Thus, $N'(\mathrm{C}^+)\ n(\mathrm{e})/N(\mathrm{C}^0) = \Gamma/\alpha$, where Γ is the ionization rate per C^0 atom due to the combined galactic and stellar ultraviolet radiation field and α is the recombination coefficient calculated for both 47 and 76 °K. If the distance of the clouds from δ Sco is 10 pc then $n(\mathrm{e})/n(\mathrm{H})$ is 2.1×10^{-4} for $T = 47$ K and 4.8×10^{-4} for $T = 76$ K. Uncertainties in the column densities result in a decrease from these values by a factor of 2 and an increase by a factor of 7. The large positive uncertainty arises when the C II (1335.7 Å) line correction is not made. The quoted values may also be decreased by a factor of 2 if the clouds are so located that the stellar radiation field is no longer an important source of ionizing radiation. If the density of the intercloud hydrogen along the line of sight is 0.07 hydrogen atoms cm^{-3} and the hydrogen is not more than 50 % ionized, then the correction to be made to $n(\mathrm{e})/n(\mathrm{H})$ taking into account intercloud hydrogen atoms and C^+ ions amounts to less than a factor of 1.1, and consequently, was ignored.

If the ionizing radiation is confined to wavelengths greater than 912 Å and cosmic rays or X-rays are unimportant in this respect, then the conventional ratio of electron donors to hydrogen atoms including those in H_2 molecules is *ca.* 4.5×10^{-4}. There is rather good agreement between the deduced value of $n(\mathrm{e})/n(\mathrm{H})$ for $T = 76$ K and the conventional ratio whereas $n(\mathrm{e})/n(\mathrm{H})$ for $T = 47$ K is about a factor of 3 less than the conventional value. These results appear reasonable in the light of figure 2 which leads one to expect a depletion of electron donors by a factor of *ca.* 2 presumably due to adsorption of atoms onto grain surfaces. An independent observation of six OB stars in the direction of Orion and Cassiopeia carried out by Boksenberg *et al.* (1972) provides results which are useful for comparison purposes. In this work the authors determined the interstellar cloud electron density from observations of the Mg II (2795.53, 2802.70 Å) and Mg I (2852.13 Å) lines obtaining an average value of $n(\mathrm{e})$ for five of the six stars equal to $2.8 \times 10^{-3}\ \mathrm{cm}^{-3}$. If it is assumed that the interstellar clouds along the line of sight to these stars are the 'standard' variety, i.e. $n(\mathrm{H}) = 10\ \mathrm{cm}^{-3}$, then $n(\mathrm{e})/n(\mathrm{H}) = 2.8 \times 10^{-4}\ \mathrm{cm}^{-3}$, which is close to the value reported here.

In conclusion, it appears that the derived characteristics of the δ Sco interstellar clouds are relatively self-consistent and do not challenge our expectations except in one important respect, and that is, of course, the overabundance of the heavy elements of silicon and iron.

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