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Determination of stellar and interstellar abundances from weak absorption lines

ABSTRACT

In this paper we discuss how accurate interstellar gas phase element abundances may be derived using weak absorption lines in the spectra of early-type stars, providing both the interstellar line strength and the corresponding f-value have been reliably determined. We also discuss an analogous method for estimating cosmic abundances using weak *stellar* absorption lines in the spectra of main sequence early-type stars. Such stellar atmospheres should be uncontaminated by the products of interior nuclear reactions. As the stars will also have short lifetimes, the stellar abundances should reflect the current chemical composition of the solar neighborhood.

INTRODUCTION

A major area of astronomical research for several decades has been the study of the diffuse interstellar medium (see, for example, Cowie and Songaila 1986, Harris 1988 and references therein), which consists of gas and dust grains. One important method for observing the gas phase material is through the absorption lines it produces in the optical and UV spectra of early-type stars (Bohlin *et al.* 1983, Joseph *et al.* 1985). Of particular interest is the chemical composition of the dust, which may be inferred from the *depletions* of the elements observed in the gas phase (see, for example, York *et al.* 1983). The depletion d_i of an element is defined by (Shull 1986):

$$\log d_i = \log(N_i/N_H) - \log (N_i/N_H)_\odot$$

where (N_i/N_H) and $(N_i/N_H)_\odot$ are the relative abundance of element i to hydrogen in the interstellar medium, and the cosmic abundance, respectively. Values of N_H can be determined to an accuracy of approximately 10% from $L\alpha$ and H_2 absorption lines (Bohlin *et al.* 1978, Savage *et al.* 1977, Shull and Van Steenberg 1985). In this paper we discuss how reliable interstellar and cosmic (stellar) abundances may be estimated through the analysis of absorption lines with small oscillator strengths.

INTERSTELLAR ABUNDANCES

Interstellar abundances are normally estimated using a curve of growth with a single Maxwellian velocity distribution, in which the derived abundance depends on the absorption line strength (denoted by the equivalent width W_λ), the velocity distribution of the line of sight interstellar material (characterised by a Doppler width b), and the oscillator strength f of the transition under consideration (Spitzer 1978). However for absorption lines with small oscillator strengths ($f \leq 10^{-2}$), the derived element abundance for most sightlines depends exclusively on the measured interstellar absorption line strength and f-value and not on the adopted b-value. To determine accurate abundances one therefore needs reliable estimates of these two quantities.

Bohlin *et al.* (1983) have published a survey of ultraviolet interstellar absorption lines in the spectra of 88 early-type stars, obtained with the Princeton high resolution (~0.05Å FWHM) spectrometer on board the *Copernicus* satellite (Rogerson *et al.* 1973). These observations cover the wavelength range 950–1370Å, and include highly reliable equivalent widths for many weak absorption lines in species such as N I and O I. For example, for the N I 1161Å line in the line of sight to β^1Sco, Bohlin *et al.* find $W_\lambda = 3.2\pm0.5$mÅ, while for O I 1356Å towards κ Ori, $W_\lambda = 3.1\pm0.3$mÅ. More recently, Van Steenberg and Shull (1988a) have extended the work of Bohlin *et al.* by publishing a survey of interstellar line strengths in the wavelength range 1097–2605Å towards 261 early-type stars, obtained with the lower resolution (~0.2Å FWHM) spectrographs on board the *International Ultraviolet Explorer* (IUE) satellite (Boggess *et al.* 1978). Although the IUE observational data are not as good as those from *Copernicus*, due to lower resolution and signal-to-noise capabilities, IUE can observe much fainter stars. Moreover in the future very high quality observations of faint stars should be available from the very high resolution (~0.01Å FWHM) spectrometers on board the *Space Telescope* (see Gull *et al.* 1986 and references therein).

Over the past few years there have been several studies of interstellar abundances using the absorption lines in the Bohlin *et al.* (1983) *Copernicus* and Van Steenberg and Shull (1988a) IUE surveys. These include York *et al.* (1983) for the elements N and O, Harris and Bromage (1984) for Cl, Jenkins *et al.* (1986) for Mg, P, Cl, Mn, Fe, Cu and Ni, Harris and Mas Hesse (1986) for S, Harris (1987) for Fe, P and S, and Van Steenberg and Shull (1988b) for Si, Mn, Fe, S and Zn. However in general these authors used oscillator strengths taken from the literature (and particularly the compilation of Morton and Smith 1973). In many cases, the wavefunction had not been optimised for the transition of interest and hence the corresponding f-value was not reliable. At Queen's University Belfast we therefore embarked on an extensive project in 1983 to calculate accurate f-values using the CIV3 code of Hibbert (1975) for the transitions observed by Bohlin *et al.* (The methods employed by Hibbert to determine f-values are discussed by him elsewhere in these proceedings). To date, interstellar abundances accurate to normally ±0.1 dex have been derived for magnesium (Murray *et al.* 1984), nitrogen (Hibbert *et al.* 1985), oxygen (Keenan *et al.* 1985) and phosphorous (Dufton *et al.* 1986), while work on chlorine is in progress. Our results are significantly different from those of previous authors, and imply effectively zero depletions for low density sightlines, consistent with such sightlines generally having little interstellar dust content (Keenan *et al.* 1986).

In the future we intend to extend our work to calculate f-values for other species in the Bohlin *et al.* (1983) survey, including Fe II, Cu II and Ni II. We also plan to produce atomic data relevant to *Space Telescope* observations.

COSMIC ABUNDANCES

As noted in the previous Section, the combination of high quality interstellar absorption line strengths and accurate f-values allows extremely reliable interstellar abundances to be derived. For example, towards ζ Oph the oxygen abundance is known to ±0.04 dex (Keenan *et al.* 1985). However as pointed out in the Introduction, an important quantity in interstellar medium studies is the element *depletion*, as from this the grain composition is inferred. Hence an accurate knowledge of the *cosmic abundance* value of the element under consideration is also required. Unfortunately, cosmic abundances employed in interstellar work are usually determined from the sun and meteorites, and are often uncertain (Grevesse 1984, Meyer 1985a,b), thereby vitiating the accuracy of the interstellar depletions. Furthermore, cosmic abundances determined in this way apply to the interstellar medium as it was in the solar neighbourhood some 5×10^9yrs ago, and hence are not necessarily appropriate to studies of current depletions.

At Queen's we have therefore recently undertaken a programme to derive accurate *contemporay* cosmic abundances using a similar approach to that employed in the interstellar work described above. Weak *stellar* absorption lines (with typical equivalent widths of 5mÅ) are observed in the spectra of main sequence early-type stars. Due to their weakness, these lines have equivalent widths which are very sensitive to the element abundance, but not to the assumptions made in the model atmosphere analysis.

We have initially observed weak lines of argon as as the cosmic abundance of this element is particularly uncertain (Grevesse 1984, Meyer 1985a,b), and it has been extensively detected in the interstellar medium through absorption lines of A I at 1066.7 and 1048.2Å (see Duley 1985 and references therein). Observational data were obtained using the coudé spectrograph with a CCD detector on the Coudé Feed Telescope at the Kitt Peak National Observatory in December 1988 (see Keenan *et al.* 1990 for more details). For γ Peg, δ Cet and HR 1765 the 4587–4611Å wavelength region was observed, which includes the A II line at 4589.98Å. In addition, spectra covering the wavelength interval 4647– 4672Å (which contains the A II line at 4657.94Å) were obtained for γ Peg. In Figure 1 we show the spectrum of γ Peg from 4585–4605Å to illustrate the high quality of the observational data. The equivalent widths found for the A II 4590 and 4658Å lines were in the range 5–7mÅ, with errors of typically ±0.5mÅ.

The observational data were analysed by comparing measured stellar Strömgren colours (effective temperature indicators), β indices (surface gravity indicators) and A II equivalent widths with those predicted by local thermodynamic equilibrium (LTE) model atmosphere codes. All theoretical results were deduced using the line blanketed grid of models of Kurucz (1979), or new models calculated with Kurucz's program. The derivation of effective temperatures and surface gravities have been discussed in detail by Keenan *et al.* (1990).

Using the stellar atmospheric parameters, argon abundances were deduced by comparing the observed A II line strengths with those predicted from LTE model atmosphere calculations (see Brown *et al.* 1986 for more details). A microturbulent velocity $V_t = 5 \pm 5 \text{kms}^{-1}$ was adopted for the all the stars, as this value has been found to be appropriate for LTE analyses of near main sequence early-type stars (see, for example, Hardorp and Scholz 1970; Kodaira and Scholz 1970); however for the programme stars the derived A II abundances are effectively independant of the choice of V_t (see below). Oscillator strengths for the A II 4590 and 4658 Å transitions were taken from Garcia and Campos (1985), who measured A II lifetimes (and hence f-values) to an accuracy of better than 10% using the delayed-coincidence method.

In Table 1 the derived argon abundances log [A] (on the scale log [H] = 12) are summarised, along with the changes in log [A] (Δlog [A]) found when *all* the observational uncertainties (equivalent widths *and* atmospheric parameters) are taken into account. An inspection of the table shows that the results are relatively insensitive to the observational uncertainties, and the derived values of log [A] should be accurate to approximately ±0.05 dex. Support for this comes from the fact that for the three stars the derived argon abundances are in excellent agree-

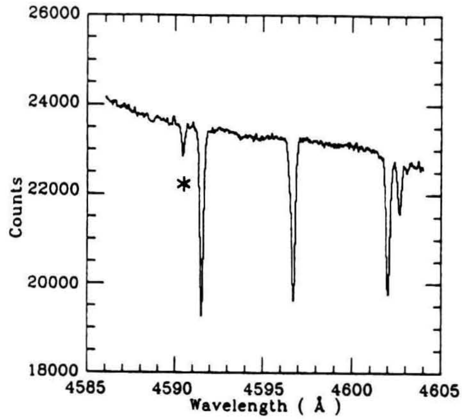

Fig. 1. The spectrum of γ Peg from 4585–4605Å, which clearly shows the weak A II line at 4590Å (marked with an asterisk). This feature has an equivalent width of W_λ = 6.3±0.5mÅ.

ment, with discrepancies of typically 0.05 dex, while for γ Peg the values of log [A] estimated from the two A II lines differ by only 0.07 dex.

For the three stars we obtain a mean abundance of log [A] = 6.49±0.04, where the error bar refers to the sample standard deviation. There is also an uncertainty in log [A] which arises from possible non-LTE effects. However very recent non-LTE calculations for A II performed by us (Holmgren *et al.* 1990) indicate that these effects should be small (≤0.02 dex) for the transitions under consideration. In view of this, and the fact that there is a possible 10% uncertainty in the adopted A II f-values (Garcia and Campos 1985), we therefore conclude that our mean argon abundance should be accurate to ±0.05 dex.

Table 1. Derived stellar argon abundances, on the scale log [H] = 12

Star	Line (Å)	log [A]	Δlog [A]
γ Peg	4590	6.50	±0.03
γ Peg	4658	6.43	±0.09
HR 1765	4590	6.53	±0.08
δ Cet	4590	6.49	±0.03

As the stars under consideration are on or near the main sequence, their atmospheres should be uncontaminated by the products of interior nuclear reactions (Brown *et al.* 1986), and hence any derived abundances should reflect those of the interstellar material from which the stars formed some 10^6–10^7yrs ago. During these short lifetimes it is unlikely that the stars have moved significantly from their places of origin, and as they lie within typically 500pc of the sun (Savage *et al.* 1985), our result of log [A] = 6.49±0.05 therefore represents an *accurate* evaluation of the *current cosmic* abundance value of argon in the solar neighborhood.

As argon is not present in the solar photospheric spectrum (see, for example, Grevesse 1984), previous estimates of the cosmic abundance value have been determined from emission lines formed in the solar corona, which are detected in the X-ray region of the spectrum. In these analyses most authors have calculated argon abundance *ratios* (for example A/Fe; Doschek *et al.* 1985), and used the solar abundance of the denominator to infer that for argon. Using this method, Withbroe (1971), Walker *et al.* (1974) and Doschek *et al.* have determined values for log [A] of 6.65, 6.78 and 6.44, respectively, with error estimates of approximately ±0.2–0.3 dex. According to Meyer (1985b), the only *absolute* argon abundance determination is that of Veck and Parkinson (1981), who found log [A] = $6.38^{+0.18}_{-0.30}$ from an analysis of solar flare data from the OSO-8 satellite. These authors were able to measure the absolute abundance as they analysed not only the A XVII line emission at ~4Å, but also the continuum emission, which is dominated by free-free and free-bound processes in hydrogen. We note that our result is in good agreement with that of Veck and Parkinson, and also with the recent measurement by Doschek *et al.* However the error estimate in our argon abundance is 12% or less, as opposed to the ≃75% uncertainty in those of Veck and Parkinson and Doschek *et al.*

It is interesting to note that although up to now the most reliable cosmic argon abundance estimate is the log [A] = 6.38 of Veck and Parkinson (1981), many workers have adopted the Withbroe (1971) value of log [A] = 6.65 in interstellar depletion studies of argon (see, for example, York 1983, Duley 1985). For the sightlines to λ Sco and α Vir, York (1983) and York and Kinahan (1979) found argon depletions of ~0.20 and ~0.15 dex, respectively, using the Withbroe cosmic abundance value. However adoption of the present result implies that argon is effectively undepleted in these sightlines, which is to be expected as they are unreddened and hence contain few interstellar grains (see Keenan *et al.* 1986).

In the future we plan to extend our work by observing weak absorption lines of P II in early-type stellar spectra, as this species is extensively observed in the interstellar medium (Dufton *et al.* 1986), and accurate oscillator strength calculations performed at QUB are available (Hibbert 1988).

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