Sulphur is the tenth most abundant element in the Universe and plays an important role in studies of the chemical enrichment and star-formation history of distant galaxies. Due to the lack of suitable sulphur lines in the visible part of stellar spectra there is, however, still no agreement on the abundance of sulphur in Galactic metal-poor stars, and we are therefore uncertain about the nucleosynthetic origin of sulphur. New observations of infrared sulphur lines with the cryogenic high-resolution infrared echelle spectrograph (CRIRES) at ESO’s VLT are helping to solve this problem.

Abundance ratios of elements in celestial objects are usually given on a logarithmic scale with the corresponding solar ratio as the zero point. From the ratio between the number of iron and hydrogen atoms, we define the metallicity of a star as [Fe/H] = \log(N_{\text{Fe}}/N_{\text{H}})_\text{star} - \log(N_{\text{Fe}}/N_{\text{H}})_\text{Sun}, and in order to get information on the nucleosynthesis of an element X, we are studying how the quantity [X/Fe] = \log(N_{X}/N_{\text{Fe}})_{\text{star}} - \log(N_{X}/N_{\text{Fe}})_{\text{Sun}} varies as a function of [Fe/H]. For example, one finds that magnesium has a constant overabundance [Mg/Fe] = +0.3 dex (corresponding to a factor of two) in Galactic halo stars with metallicities in the range −4 < [Fe/H] < −1, whereas [Mg/Fe] declines continuously to zero in disc stars with −1 < [Fe/H] ≤ 0. A similar trend is found for [Si/Fe]. This can be explained if Mg and Si are made primarily by α-capture reactions (i.e. successive captures of α-particles) in Type II supernovae (SNe), whereas iron is made by silicon burning in both Type Ia and Type II SNe. The point is that Type Ia SNe are not contributing with iron until the disc phase of our Galaxy, because their occurrence is delayed by about one billion years relative to Type II SNe, due to the lower progenitor mass of Type Ia SNe.

Sulphur is an element with an even number of protons (Z = 16) like Mg and Si (Z = 12 and 14), and nucleosynthesis calculations predict that S is made in the same way as Mg and Si in Type II SNe. Hence, we expect [S/Fe] to have the same trend with [Fe/H] as [Mg/Fe] and [Si/Fe]. Sulphur abundances derived from the weak Si line at 869.5 nm by Israelian and Rebolo (2001) and Takada-Hidai et al. (2002) showed, however, an increasing trend of [S/Fe] towards low metallicities, with [S/Fe] reportedly reaching values as high as +0.8 dex (a factor of six higher than the S/Fe ratio in the Sun) at [Fe/H] = −2.0. They suggested that such high S/Fe ratios might be due to an enhanced sulphur production in supernovae with a very large explosion energy, so-called hypernovae. Nissen et al. (2004), on the other hand, used the stronger Si lines at 921.3 and 923.8 nm to derive a near-constant [S/Fe] ~ +0.3 for halo stars in the metallicity range −3 < [Fe/H] < −1, as expected if normal Type II SNe are the sole source of sulphur. More recently, Caffau et al. (2005) proposed a dichotomy of [S/Fe] among Galactic halo stars with both high and low [S/Fe] values, which would imply a very complicated evolution of the sulphur abundance in our Galaxy.

A reason for the diverging [S/Fe] results may be that errors in determining sulphur abundances are larger than claimed by the authors of the cited papers. In this connection, we note that the 869.5 nm Si line is very weak in metal-poor halo stars and hence the measured strength of the line may be affected by irregular fringing variations of the CCD detector response, which are difficult to correct by flat-fielding. The stronger r lines at 921.3 and 923.8 nm are less affected by such errors, but they occur in a spectral region hampered by numerous telluric lines that are often blended with the sulphur lines.

Figure 1: The CRIRES spectrum of the metal-poor ([Fe/H] = −1.7) dwarf star G29-23 around the 1.046 μm S triplet (dots) compared with synthetic model-atmosphere line profiles for three sulphur abundances corresponding to [S/Fe] = 0.0, +0.3 and +0.6, respectively.
better than our earlier UVES spectrum of the same star (observed under similar conditions and with the same exposure time), which has S/N ~ 200 around the Si lines at 921.3 and 923.8 nm. Furthermore, unlike the UVES near-IR spectrum, the CRIRES spectrum at 1.046 μm is not plagued by telluric lines and fringing residuals.

The CRIRES spectrum of G29-23 is shown in Figure 1 in comparison with synthetic profiles of the sulphur lines for three values of [S/Fe]. Details of the model-atmosphere calculations and the determination of the iron abundance, which is based on Feii lines, can be found in Nissen et al. (2007). As can be seen from the Figure, the synthetic profile corresponding to [S/Fe] = +0.3 provides an excellent fit to the CRIRES data for all three Si lines.

**Comparison with UVES observations**

In Figure 2, the UVES spectrum of G29-23 is shown for the sulphur lines at 869.5, 921.3 and 923.8 nm. Telluric lines were removed by dividing by a scaled B-type star spectrum as described in Nissen et al. (2007). Again, the synthetic profile corresponding to [S/Fe] = +0.3 fits the data very well, but it is clear that the [S/Fe] value obtained from the weak 869.5 nm line is rather uncertain.

Although one should not put too much weight on a single star, the CRIRES spectrum of G29-23 provides an important check of the sulphur abundances obtained from UVES spectra for 40 halo stars by Nissen et al. (2007). As shown in the upper panel of Figure 3, the UVES data indicate that [S/Fe] lies around a plateau of +0.3 dex if local thermodynamic equilibrium (LTE, i.e. a Boltzmann distribution of the atoms over the possible atomic energy states) is assumed when deriving the S abundances. If non-LTE corrections based on the statistical equilibrium calculations of Takeda et al. (2005) are taken into account, the plateau decreases to about +0.2 dex as shown in the lower panel of Figure 3.

The scatter of [S/Fe] around this plateau is remarkably small, ±0.07 dex only, and no star has an enhanced S/Fe ratio...
cool halo giants may be particularly helpful in this connection. This line is formed close to LTE in cool stars, because nearly all sulphur atoms are in the lower energy level of the line (the ground state of the Si atom), and the number of atoms in the upper level is determined by collisions rather than radiative transitions. The forbidden line is very weak, but thanks to the efficiency and high resolution of CRIRES, precision measurements will be possible at metallicities as low as [Fe/H] ~ –2.5.

References
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[S/Fe] > +0.60) as claimed by Israelian and Rebolo (2001), Takada-Hidai et al. (2002) and Caffau et al. (2005). Our results suggest that sulphur in the Galactic halo was made in the same way as Mg and Si, i.e. by α-capture processes in massive SNe.

The S/Zn ratio of Damped Lyman-alpha systems

The sulphur abundances derived by Nissen et al. (2007) were combined with zinc abundances determined from the 472.2 and 481.1 nm Zn lines. Both S and Zn are among the few elements which are not readily depleted onto dust in the interstellar medium. For this reason, they are key to studies of metal enrichment in distant galaxies, particularly those detected as damped Lyman-alpha systems (DLAs) in the spectra of high-redshift quasars. Assuming that sulphur behaves like other α-capture elements and that Zn follows Fe, the S/Zn ratio has been used to estimate the timescale of the star-formation process in DLAs. In particular, it has been argued that a solar S/Zn ratio indicates that Type Ia SNe have contributed to the chemical enrichment and that the age of a DLA system with a solar-like S/Zn therefore must be at least one billion years.

Before such a conclusion can be made, it is important to clarify the trend of [S/Zn] among Galactic stars. Figure 4 shows the results from Nissen et al. (2007). It is found that the trend of [S/Zn] depends quite critically on whether LTE is assumed or not. When the non-LTE corrections of Takeda et al. (2005) are applied, there is an overall decrease in [S/Zn] at all but the highest values of [Zn/H] considered here. Furthermore, non-LTE effects are most significant at low metallicities with the result that, apparently, [S/Zn] reverts to solar values when [Zn/H] < –2.

Such behaviour is unusual but, given our current limited understanding of the nucleosynthesis of Zn, cannot be excluded.

Taken at face value, the lack of a strong metallicity trend in the lower panel of Figure 4 would indicate that the usefulness of the S/Zn ratio as a ‘clock’ of the star-formation history is rather limited. The question that remains concerns the accuracy of the non-LTE calculations by Takeda et al. (2005); they depend critically on the rather uncertain cross-section for inelastic collisions with neutral hydrogen atoms, which tend to enforce an LTE population of the energy levels (Asplund 2005). Future observations of the forbidden sulphur line at 1.082 μm in...