Sulphur Abundances in Metal-Poor Stars – First Result from CRIRES Science Verification

Poul Erik Nissen[1]
Martin Asplund[2]
Damian Fabbian[2]
Florian Kerber[3]
Hans Ulrich Käufl[3]
Max Pettini[4]

[1] Department of Physics and Astronomy, Aarhus University, Denmark
[2] Research School of Astronomy and Astrophysics, Australian National University
[3] ESO
[4] Institute of Astronomy, University of Cambridge, United Kingdom

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 $[\mathrm{Fe/H}] \equiv \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\mathrm{Star}} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\mathrm{Sun}}$, and in order to get information on the nucleosynthesis of an element X, we are studying how the quantity $[\mathrm{X/Fe}] \equiv \log(N_{\mathrm{X}}/N_{\mathrm{Fe}})_{\mathrm{Star}} - \log(N_{\mathrm{X}}/N_{\mathrm{Fe}})_{\mathrm{Sun}}$ 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 S I 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 S I 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 S I 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 I 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.

CRIRES observations

CRIRES is a cryogenic, infrared echelle spectrograph designed to provide a resolving power λ/Δλ of up to 100 000 between about 950 nm and 5 000 nm as described in detail by Käufl et al. (2006). The commissioning of this VLT instrument opens up a new opportunity for independent determinations of sulphur abundances in metal-poor stars based on high-resolution observations of the S I triplet at 1.046 μm. As part of the science verification of CRIRES, a spectrum around the infrared triplet was obtained for the halo dwarf star G29-23 (V = 10.19, [Fe/H] = −1.7) on 6 October 2006. The entrance slit width of CRIRES was set at 0.4 arcsec, which corresponds to a resolving power of 50 000 with four detector pixels per spectral resolution bin Δλ. In order to improve the removal of sky emission and detector dark current, the observations were performed in nodding mode with a shift of 10 arcsec between the two settings of the star on the slit. The exposure time was 2 400 s. The seeing was rather poor (about 1.3 arcsec) but adaptive optics was applied to improve the stellar image, and the combined spectrum has a very satisfactory signal-to-noise ratio S/N ~ 330 per spectral dispersion pixel. This is considerably

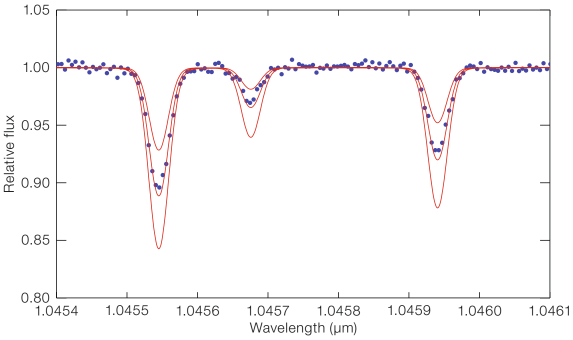

Figure 1: The CRIRES spectrum of the metal-poor ([Fe/H] = −1.7) dwarf star G29-23 around the 1.046 μm S I triplet (dots) compared with synthetic model-atmosphere line profiles for three sulphur abundances corresponding to [S/Fe] = 0.0, +0.3 and +0.6, respectively.

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 S I 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 Fe II 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 S I 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

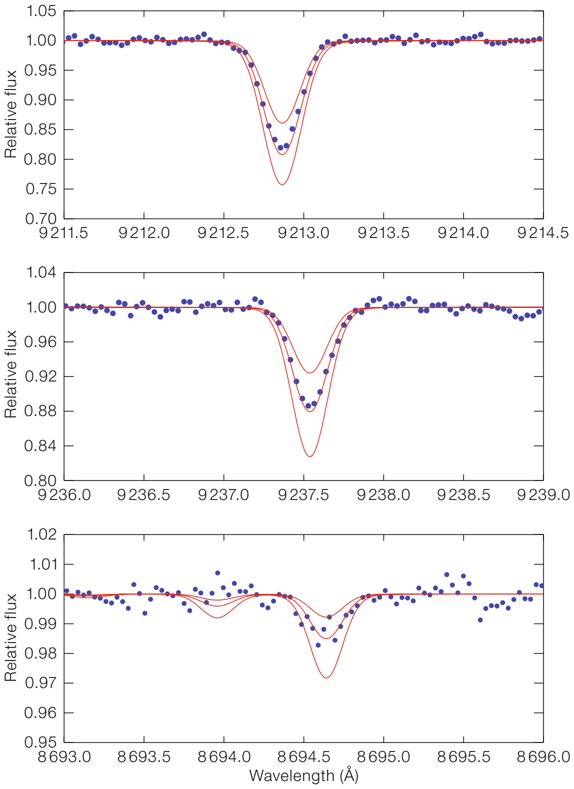

Figure 2: The UVES spectrum of G29-23 around the S I lines at 921.3, 923.8, and 869.5 nm (dots) compared with synthetic line profiles for three sulphur abundances corresponding to [S/Fe] = 0.0, +0.3 and +0.6, respectively.

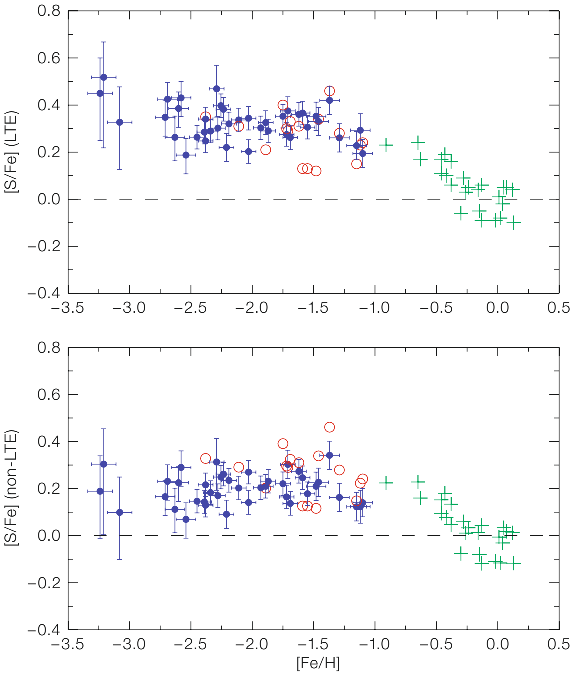

Figure 3: [S/Fe] *versus* [Fe/H] for Galactic stars. Disc stars ([Fe/H] > −1) from Chen et al. (2002) are shown with green crosses. For the halo stars ([Fe/H] < −1), blue circles with error bars show data based on sulphur abundances derived from the 921.3, 923.8 nm S I lines, and red circles show data from the weak 869.5 nm S I line. In the upper panel LTE has been assumed in deriving the S abundances, whereas the lower panel includes non-LTE corrections from Takeda et al. (2005).

([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 I 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 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 S I 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

Asplund M. 2005, ARA&A 43, 481
Caffau E. et al. 2005, A&A 441, 533
Chen Y. Q. et al. 2002, A&A 390, 225
Israelian G. and Rebolo R. 2001, ApJ 557, L43
Käufl et al. 2006, The Messenger 126, 32
Nissen P. E. et al. 2004, A&A 415, 993
Nissen P. E. et al. 2007, A&A 469, 319
Takada-Hidai M. et al. 2002, ApJ 573, 614
Takeda Y. et al. 2005, PASJ 57, 751

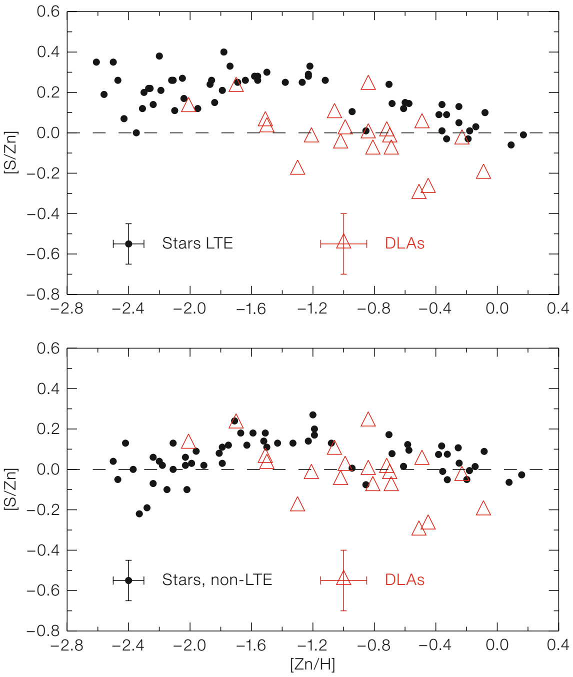

Figure 4: [S/Zn] *versus* [Zn/H] for Galactic stars and damped Lyman-alpha systems. Typical 1-σ error bars are shown. In the upper panel the stellar S and Zn abundances have been derived assuming LTE, whereas the lower panel includes non-LTE corrections from Takeda et al. (2005).