Solar Chemical Peculiarities?

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Several investigations of FGK stars in the solar neighborhood have suggested that thin-disk stars with an iron abundance similar to the Sun appear to show higher abundances of other elements, such as silicon, titanium, or nickel. Offsets could arise if the samples contain stars with ages, mean galactocentric distances, or kinematics, that differ on average from the solar values. They could also arise due to systematic errors in the abundance determinations, if the samples contain stars that are different from the Sun regarding their atmospheric parameters. We re-examine this issue by studying a sample of 80 nearby stars with solar-like colors and luminosities. Among these solar analogs, the objects with solar iron abundances exhibit solar abundances of carbon, silicon, calcium, titanium and nickel.

1. Introduction

Under the assumption that low-mass dwarf stars with convective envelopes have a surface chemical composition which simply reflects that of their natal clouds, one can use such stars to trace the chemical evolution of the Galaxy. The Sun is then a convenient reference, but are there nearby stars with solar composition? or in other words, is the solar abundance pattern the norm in the local thin disk?

Inspection of some of the most recent synoptic studies of nearby stars suggests that the Sun’s metallicity is slightly off from average (metallicity is here equated to the iron abundance [Fe/H]). Nordström et al. (2004) obtained metallicities from Strömgren photometry for nearly 14,000 F- and G-type stars within 70 pc, finding that their distribution could be approximated by a Gaussian with a mean of [Fe/H] = −0.14 and a σ of 0.19 dex. Allende Prieto et al. (2004) studied spectroscopically the stars more luminous than $M_V = 6.5$ ($M > 0.76 M_\odot$) within 14.5 pc from the Sun and concluded that their metallicity distribution is centered at [Fe/H] = −0.11 and has a σ of 0.18 dex. Luck & Heiter (2005) derived spectroscopic metallicities for a sample of 114 FGK stars within 15 pc (similar to that analyzed by Allende Prieto et al. 2004), finding a metallicity distribution with a consistent width (σ = 0.16 dex), but centered at a value slightly closer to solar (−0.07 for the complete sample, and −0.04 when thick-disk stars are excluded). Haywood (2002) has argued that sample selection based on spectral type discriminates against high-metallicity stars, proposing a metallicity distribution for the solar neighborhood (based on photometric indices) that is centered at the solar value.

Inevitably, one must ask whether there is any reason to expect the local metallicity distribution to be centered at the solar value. Chemical differences among the Sun and its neighbors may be reasonable if the age or the Galactic orbit of the Sun are somewhat off from the average for nearby stars. The age distribution or, equivalently, the star formation history of the solar neighborhood is an unsolved problem, judging from the discrepant results obtained from analyses of the Hipparcos H-R diagram (Bertelli & Nasi 2001, Vergely et al. 2002) and studies of stellar activity (e.g. Rocha-Pinto et al. 2000).

What about abundance ratios? Should we expect the ratios such as C/Fe to be fairly uniform at any given iron abundance? Chemical uniformity requires the interstellar

$\dagger$ \([Fe/H] = \log_{10} \frac{N(Fe)}{N(H)} + 12\), where \(N\) represents number density
medium to be extremely well mixed, but that is precisely what local spectroscopic studies find. Reddy et al. (2003) examined this issue based on high-dispersion spectra of a few hundred stars and were unable to detect any cosmic scatter. The dispersion was as small as 0.03-0.04 dex for many elements, and could be entirely accounted for considering the uncertainties in the atmospheric parameters. The immediate implication is that the local interstellar medium is well mixed and has been well mixed for many Ga. Such a conclusion is not contradicted by studies of interstellar gas towards bright stars within and beyond the local bubble (e.g. Oliveira et al. 2005).

In this situation it seems only natural to expect the Sun to show similar abundance ratios as other low-mass dwarfs in the solar vicinity with similar metallicity. That is indeed the case for most elements, but there are some striking offsets. The landmark study by Edvardsson et al. (1993) found nearby FGK-type stars with solar iron abundance to be, on average, richer than the Sun in Na, Al, and Si. Part of this trend, but not all, could be linked to biases in other stellar parameters, such as mean galactocentric distance and age. More recent studies of nearby low-mass stars kept finding offsets between the abundance ratios of stars with solar iron abundances and the Sun. For example, Reddy et al. (2003) found small offsets, in the same sense as Edvardsson et al. for the ratios C/Fe, N/Fe, K/Fe, S/Fe, Al/Fe, and Si/Fe (and perhaps Na/Fe), but opposite trends for Mn/Fe and V/Fe. Allende Prieto et al. (2004) also found similar patterns in their sample for O/Fe, Si/Fe, Ca/Fe, Sc/Fe, Ti/Fe, Ni/Fe, and some neutron-capture elements (Na was not studied).

The lack of consistency among different studies regarding the existence and size of these chemical offsets is worrisome. Local samples of stars span variable ranges in spectral type, which may be associated with different systematic errors. In order to explore further the nature of the observed offsets we have observed a sample of solar analogs selected from the Hipparcos color-magnitude diagram. We described the results below.

2. Data and analysis

To select solar analogs we used the Johnson $M_V$ absolute magnitudes and the $(B-V)$ color indices compiled by Allende Prieto & Lambert (1999) for 17,219 nearby stars $(d < 100$pc) included in the Hipparcos catalog. Stars were selected to be within 0.07 mag from the adopted values for the Sun $(B-V, M_V) = (0.65, 4.85)$ and to be accessible to the 9.2m Hobby-Eberly Telescope (HET) at McDonald Observatory during the first observing period of 2005 (December 2004–March 2005), when the observations were obtained. A list of 130 stars were placed on the HET queue, and 94 were spectroscopically observed.

The observations employed the High Resolution Spectrograph (HRS, Tull 1998), a fiber-coupled spectrograph, using the first-order diffraction grating g316 as cross disperser to get almost continuous coverage between 407.6 and 783.8 nm. A fiber with a diameter of 2 arcsec fed the 0.625 arcsec wide slit of the spectrograph, providing a FWHM resolving power of $R \sim 120,000$. The data reduction was made with an automated pipeline within IRAF, performing bias correction, flat-fielding, scattered-light correction, extraction, and wavelength calibration based on Th-Ar hollow-cathode spectra.

The stellar effective temperatures, surface gravities, and overall metallicity were derived by a $\chi^2$ fitting of the spectral order containing Hβ (Allende Prieto 2003). First, the procedure was applied to the spectra of FG dwarfs included as part of the Elodie library at a resolving power of $R \sim 10,000$, then the residuals were fit by linear trends. After applying the linear corrections, the rms scatter between our results and those in the Elodie catalog are 1.5 %, 0.16 dex and 0.07 dex for $T_{\text{eff}}$, log $g$, and [Fe/H], respectively.

The HRS spectra were processed in exactly the same manner, after smoothing them
Figure 1. Stellar parameters for the sample. Two metallicity distributions are shown: [M/H] indicates the values derived from the analysis of the spectral order that includes Hβ (used to select the model atmosphere), and [Fe/H] indicates the values subsequently derived from the analysis of equivalent widths of Fe I lines. The surface gravities shown here correspond to the spectroscopic values derived from the Hβ order, but the true gravities are likely tightly concentrated around the solar value (log g ≃ 4.437), given the narrow distribution of the sample stars in $M_V$.

A resolution $R = 10,000$, and the resulting parameters were subjected to the linear corrections inferred from the comparison with the Elodie library. Fig. 1 shows the distribution of the final atmospheric parameters. Once the basic atmospheric parameters are constrained, we measured and made use of the equivalent widths of 46 Fe I lines to derive the appropriate value of the microturbulence and the iron abundance using MOOG (Sneden 2002). The iron linelist is a subset of that described in Ramírez, Allende Prieto & Lambert (2006), and for other elements we used the same lines as Allende Prieto et al. (2004). Abundances of C, Si, Ca, Ti, and Ni were also determined assuming LTE.

3. Results and discussion

Fig. 2 shows our results for silicon and titanium. The thin and thick disk membership can be easily decided from these plots. The offset from [Si/Fe]= 0 at [Fe/H]= 0 found in several previous surveys is not apparent in the left-hand panels of Fig. 2. Similarly, the right-hand panels, do not confirm the offset found by Allende Prieto et al. (2004) for titanium, and no significant offsets were found either for carbon, calcium, titanium or nickel. This result suggests that the offsets in previous analyses were likely the result of systematic errors.

Samples of stars spanning a narrow range in atmospheric parameters are well-suited
to carry out differential studies of chemical evolution. With such samples, we can potentially minimize the impact of shortcomings in the theory of stellar atmospheres and line formation on the derived abundances, as the small scatter in the abundance ratios shown in Fig. 2 suggest.

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