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Chemical Abundances in Main Sequence Stars

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Abstract. This talk reviews recent results relevant to identifying and constraining the processes that mix and transport specific elements in the envelopes of main sequence stars.

1. Introduction

On main sequence, both stars and spectroscopists separate into three subfields: **cool stars** of $T_e < 7000$ K, often magnetically active, which provide crucial information about long-term galactic chemical evolution and (via Li, Be, B) about mixing in outer layers; **hot stars** of $T_e > 15,000$ K, often with strong winds, that must be studied with non-LTE methods, and which provide information about present chemistry across the Galaxy, but lose mass too fast to allow much separation to occur; and **tepid stars** of $7000 < T_e < 15,000$ K, which show a wild variety of surface chemistry and provide powerful probes of internal separation and mixing.

2. Methods of main sequence spectrum analysis

Chemical abundances are usually derived either from curve-of-growth methods, or from spectrum synthesis. Curve-of-growth methods are widely understood, and use easily obtained or even published data. The accuracy of abundances may be estimated from line-to-line variations. However, such methods do not handle blends or crowded spectra well. They are not suitable for analyzing stars of large $v \sin i$. The spectrum synthesis method handles blends, crowded spectra, and large $v \sin i$ easily. However, this method requires much more elaborate computational tools than curve-of-growth analysis. Furthermore, analysis is usually limited to small spectrum segments, and is thus is very sensitive to errors in atomic data.

Within a single study, the attainable abundance precision is of order 0.1 dex (±25%) for elements with numerous spectral lines. However, the results are sensitive to a number of factors that limit accuracy, and current abundance analyses are substantially more uncertain than indicated by internal errors. Sources of uncertainty include the effective temperature and gravity scales, the atomic data used (especially gf values and partition functions), and the value of microturbulence parameter ξ, among other problems. Different abundance analyses of the same star can differ by up to 0.5 dex (*a factor of 3*) in abundance even for optimal elements such as Fe (e.g. Varenne & Monier 1999, Fig. 10). This remains a serious challenge to spectroscopists.

3. Cool stars

Cool main sequence stars mostly have low $v \sin i$ and rich optical spectra, so abundances may be determined accurately. Several striking results are obtained. First, at a given value of [Fe/H], the dispersion of abundances of other elements is hardly more than the uncertainty (Edvardsson et al. 1993). As [Fe/H] decreases from solar value, relative abundances of other elements X remain tightly correlated while [X/Fe] changes gradually, but abundance tables are *very poorly* correlated with star age (Chen et al. 2000). The basic conclusion of such studies is that variations in abundance tables (except for Li, Be and B) seem to be essentially due to history of nucleosynthesis, not transport or mixing.

4. Hot stars

Important difficulties occur in the study of hot stars: most stars have large $v \sin i$; the optical lines are mostly weak; rather few elements (mainly CNO, Ne, Al, Si, S, Fe) can be studied with optical spectra; the richer UV spectra are very complex; studies of such stars routinely require NLTE methods; and strong winds occur. From abundance studies of such stars we learn that the abundances of CNO are roughly solar; however, the abundances of individual CNO elements appear to deviate by $\approx$ 0.3 –0.6 dex from solar, often going *below*. Furthermore, different studies are somewhat contradictory: Gies & Lambert (1992) find Orion stars to have generally low C but high N, while Hibbins et al. (1998) find C and N positively correlated in anti-centre stars, and Andrievsky et al. (1999) find that C is always low while N can be low or high.

Among recent advances in this field, Sigut (1999) has developed a powerful method of assessing uncertainties due to uncertain atomic data in NLTE calculations; and Fitzpatrick & Massa (1999) find that they can get very good fits of Kurucz models to IUE B star spectra, and determine T_{e}, $\log g$, ξ, [Fe/H], and reddening with good precision.

5. Tepid stars

Among the tepid stars, we find many – normal? – stars that appear to have roughly solar abundances. We also find a number of minorities, the peculiar stars, characterized by very distinctive abundances.

Normal tepid stars have rich optical spectra, but usually large $v \sin i$. The $v \sin i$ barrier has been broken: Hill (1995) has shown that precise abundances ($\pm$0.1 dex) can be derived at $v \sin i > 100$ km s^{-1} using spectrum synthesis. He finds that "normal" A stars do *not* share a single abundance table, but may vary by up to 1 dex from solar. Varenne & Monier (1999) have shown that such variations occur even within normal A stars in a single cluster, and that the scatter in abundances grows with increasing $v \sin i$. Landstreet (1998) discovered that surface velocity fields can be detected in line profiles of a tiny sample of super-low $v \sin i$ stars, and that very large velocities (several km s^{-1}) are present. Even in "normal" A stars we have valuable information about separation and mixing processes.

The metallic line (Am) stars are "peculiar" tepid stars with $7000 < T_e < 10,000$ K. They are slowly rotating non-magnetic A stars with distinctive atmospheric chemistry. These stars do *not* share a single abundance table. Richer, Michaud and Turcotte (2000) may be close to accounting for Am star abundances by combining gravitational separation with deep turbulent diffusion.

The magnetic Ap stars have the most outrageous variety of atmospheric chemical compositions of any main sequence stars. They show underabundances and overabundances that vary somewhat systematically with T_e. They often show large variations in abundance from one region of the atmosphere to another, causing spectrum variations. They have large-scale, roughly dipolar kilogauss magnetic fields. They rotate several times slower than normal A stars. Because of surface inhomogeneities, classical abundance analysis of such stars is only roughly indicative.

Recently it has become possible to observe spectra in all four Stokes parameters with the Musicos spectropolarimeter (Donati et al. 1999; Wade et al. 2000), providing fundamentally new information about the magnetic field structure. A major current interest is to *map* both field structure and abundance distribution. It is thought that abundance peculiarities and surface variations are due to competition between separation and mixing, but the mechanism by which the magnetic field strongly influences this diffusion is not yet clear.

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