ABUNDANCES IN THE GALACTIC DISK

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1. Introduction

The empirical study of the build-up of chemical abundances in the galactic disk is an important route to our understanding of the history of the Galaxy. It supplies a wealth of constraints to the models and simulations being done. There are, however, still many unanswered questions concerning the details of the abundance patterns, and many uncertainties and possibly inconsistencies in the data at hand. Ideally one would like to map the abundances of individual elements as a function of time and 3-dimensional position in the disk. The study of the ISM today and of the surfaces of individual stars as probes of the ISM from the time and position of their formation help us in this endeavour.

Here I will constrain myself to discussion of abundances and abundance gradients in the local galactic disk and continue with the scatter in these abundances, presently and historically.

2. ISM Abundances

Abundances in the current (age less than 1 Gyr) disk interstellar medium can be obtained from observations of e.g. compact H II regions, field B main sequence stars, stars in young open clusters, absorption lines in the ISM, and young planetary nebulae. The different methods do not always give the same results for objects with similar birth places, which may be due to real ISM inhomogeneities on not too large scales.

For a long time, discussions of oxygen abundances derived from B main-sequence stars have indicated that there is no or only a very weak radial abundance gradient in the galactic disk. H II regions and young planetary nebulae, on the other hand, have fairly consistently suggested an oxygen gradient of about −0.06 to −0.09 dex/kpc (lower abundances at larger

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galactocentric distances), cf. e.g. Afflerbach et al. (1997) as well as typically sub-solar O/H abundance ratios in the solar neighbourhood Costa et al. (1996). This inconsistency seems to have changed recently with the extensive analysis of B stars in the field and in open clusters by Smartt & Rolleston (1997). Their new abundances, combined with distance redeterminations, now agree very well with the "nebular" results, both as regards the absolute scale and the gradient of -0.07 ± 0.01 dex/kpc for galactocentric distances between 6 and 18 kpc.

Nebular results for C, N, Ne, S, and Ar indicate similar gradients, and are typically 0.2 to 0.3 dex lower than solar in the local disk, cf. e.g. Maciel & Köppen (1994), Esteban & Peimbert (1995), Cardelli et al. (1996), Mathis (1996), Afflerbach et al. (1997).

The low abundance suggested for e.g. carbon causes difficulties for our understanding of the interstellar extinction (Mathis 1996). There is not enough carbon to explain the total amount of extinction. This problem has been dubbed the "C/H crisis" (Kim & Martin 1996) and may also be present for other elements, why modifications are sought to the standard model of ISM dust particles – still, however, without satisfactory results (Dwek 1997).

This pattern of sub-solar abundances may not be parallelled by iron and iron-peak elements. Nissen (1988) presented Strömgren *uvby*-β photometry of solar-type stars in young open clusters. Since the metallicity [M/H] derived from the m_1 index is a direct measure of the line blanketing, which for these stars is predominantly caused by lines of iron and iron-peak elements, it is often interpreted as an iron abundance, [Fe/H][1] Fig. 1a shows the iron abundances in Nissen's 10 youngest clusters relative to the Sun. In Fig. 1b are actual iron abundances derived from solar-type dwarfs in 6 open clusters observed with high-resolution spectroscopy by Boesgaard (1989). The 5 clusters in common between the two investigations are identified by name in the figure. The agreement between the results using completely different techniques is excellent; it is only for Coma that the results differ by 0.055 dex (14%) and the error bars do not meet, which is only what one may expect from a statistical point of view. The typical iron abundance in young open clusters appears to be very close to solar: The 10 youngest clusters of Nissen have a mean metallicity [Fe/H]= $+0.04 \pm 0.02$ (error in the mean), and for the 6 Boesgaard clusters the corresponding figures are [Fe/H]= $+0.01 \pm 0.04$. The mean values of [Fe/H] for the 5 clusters in common between the investigations differ by 0.020 dex. The systematic errors are difficult to judge (a major source may be the still uncertain effective temperature scale), but they appear unlikely to be as large as 0.15 dex and

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[1] The bracket notation, [X/Y], indicates logarithmic (number-) abundance ratios relative to the Sun, e.g.: $[\mathrm{Fe/H}] = \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\mathrm{Star}} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot}$

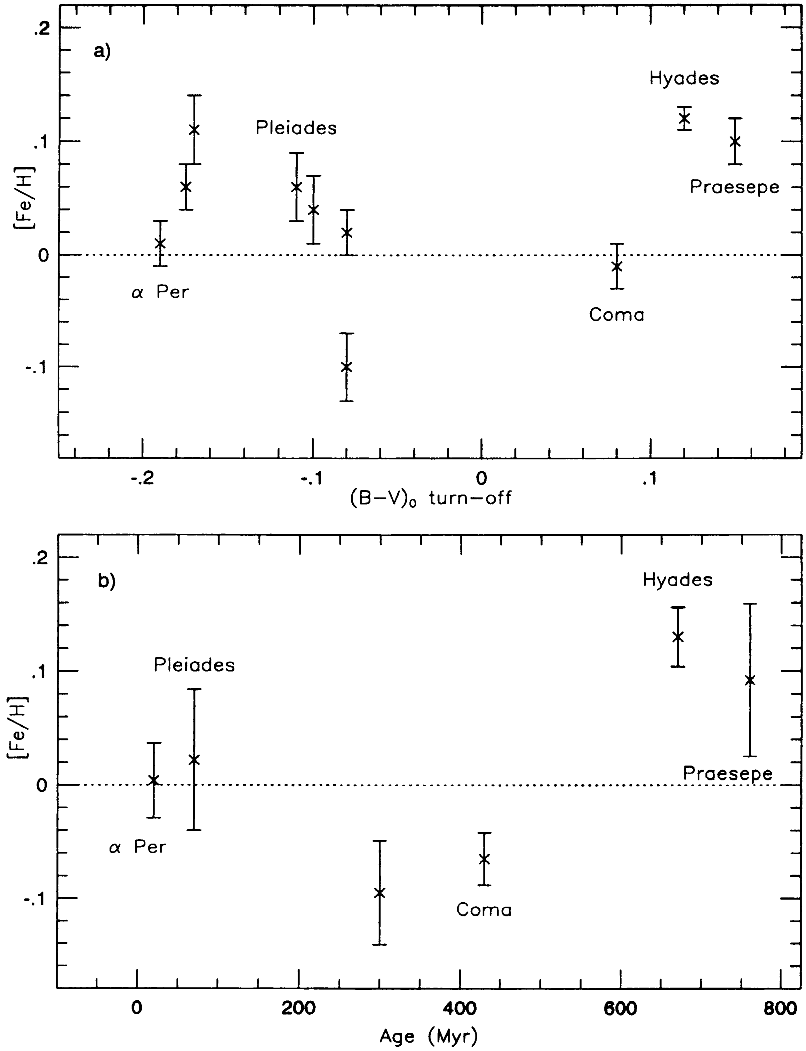

Figure 1. **Iron abundances in nearby, young open clusters. Panel a) shows metallicities (iron abundances) derived from Strömgren photometry by Nissen (1988). Panel b) shows spectroscopic iron abundances by Boesgaard (1989). Note the very good agreement for the 5 clusters in common between the two very different analyses**

are probably less than 0.10 dex considering the similarity of the stars to the relatively well known reference object called the Sun.

Taken at face value, the local ISM appears to be deficient in light elements produced in massive stars with short life times. But it is not deficient in iron, which is predominantly made in Sn Ia with longer-lived intermediate and low-mass progenitors. We don't yet know whether this difference between iron and the lighter elements is real or due to some systematic errors in the analyses. Considering the different objects and methods used to derive these abundances it would therefore be very valuable to "cross confirm" these results. To this end, carbon and oxygen abundances should be derived from G dwarfs with effective temperatures within 100 K of the Sun by means of the weak but reliable [C I] 8727 Å and [O I] 6300 Å lines, which are quite insensitive to uncertainties in effective temperatures. For the B stars, iron abundances may be derived from Fe III lines in the UV as suggested by Smartt & Rolleston (1997).

3. The ISM abundance scatter

The intrinsic scatter in the nebular abundances for objects at a certain galactocentric distance is often difficult to estimate and to disentangle from random errors in the analyses, but is probably on the order of 0.10 dex.

There are, however, young objects for which the abundance scatter is larger than the random errors in the analyses, e.g. the solar-type dwarfs in open clusters studied by Nissen (1988) and Boesgaard (1989) and discussed in the previous section (see Fig. 1). The cluster-to-cluster abundance scatter in Nissen's data is ±0.07 dex, while the relative abundances are accurate to ±0.01 to 0.03 dex. In Boesgard's sample the scatter is ±0.09 dex while the relative error bars range from 0.023 to 0.067 dex. From this I conclude that there may be abundance inhomogeneities of about 0.1 dex on physical scales of less than a kpc in the interstellar medium. It would be very interesting to find out just how small these scales really are. Is the difference mainly between spiral arm and inter-arm regions or could there be substantial abundance gradients within individual star-forming regions?

There is also some evidence that there has always been abundance scatter in the galactic disk. The sample selection in the detailed study of 189 solar-type field stars of Edvardsson et al. (1993) is biased towards low-metallicity stars and against possible old high-metallicity stars, i.e. it is not a complete volume-limited sample and should therefore not be taken as representative for the local disk population and used for studies of age-metallicity relations or the distribution of metallicities in the disk. Nevertheless, we tried to make a rudimentary volume correction, and claim that throughout the existence of the galactic disk there was always an abundance scatter of at least 0.10 to 0.15 dex in [Fe/H] for stars born at the same time and at the same galactocentric distance. An important additional result is that there is no evidence for any scatter in [α/Fe] larger than the error in the relative abundances, about ±0.05 dex (Table 17). The α elements (which are thought to be almost exclusively produced in supernovae of short-lived, massive stars; Types II, Ib and Ic) were represented by a straight mean of elements with α-element "behaviour": $[\alpha/\mathrm{H}] = \frac{1}{4}([\mathrm{Mg/H}] + [\mathrm{Si/H}] + [\mathrm{Ca/H}] + [\mathrm{Ti/H}])$. This forces the strong conclusion that any scatter of this kind CAN NOT be caused by local pollution of the ISM by e.g. bursts of star formation. While such bursts might cause local enhancements of α elements made in massive stars, they could not cause correlated enhancements of the same magnitude in iron-peak nuclei, since these are to at least 50% produced in Sn Ia with long-lived progenitors. It therefore appears unlikely that "self-pollution" in star-forming regions is an important process in the galactic disk. It was concluded that Larsson's (1972) idea of infall of metal-poor gas on the galactic disk, which would mix with and homogeneously dilute the ISM and trigger star formation is a possible mechanism to cause the scatter. Another possibility which has been suggested by Wielen et al. (1996) is that all the scatter is due to the orbital mixing of stars born at different galactocentric distances, combined with smooth radial abundance gradients in the disk. This may explain the properties of the scatter. The existence of the required orbital scatter is based on the motions of stars in the solar vicinity, but the results of Strömgren (1987) and Sommer-Larsen & Antonuccio-Delogu (1993) contradict the existence of the large velocity scatter required for this explanation. Furthermore, it is by no means clear what objects or processes might cause the required strong disturbances of stellar orbits.

The presently unclear empirical situation concerning the dynamical heating of the galactic disk may soon be clarified by the ongoing work by Nordström et al. (1998). With a homogeneous material of Strömgren *uvby*-β photometry of about 18,000 stars in the solar neighbourhood, and for a sub-sample of about 5,000 stars complete distances and proper motions, accurate radial velocities and ages determined from isochrones will be available. This will constitute an excellent data base for the study of metallicity and metallicity scatter, stellar dynamics and orbital scatter (among other issues), and should finally settle the question concerning heating and mixing of stellar orbits in the disk.

4. Conclusions

We need to confirm whether the lighter elements like C, N, O, Ne, S, Ar really are underabundant in the ISM, while iron has close to the solar abundance. The abundances of carbon and oxygen in the ISM should therefore be measured also in solar-similar dwarfs in young open clusters, while iron abundances could be derived from the UV spectra of main-sequence B stars.

The scales of abundance inhomogeneities in the local ISM should be studied by homogeneous analyses of "identical" objects within individual star-forming regions and between different ones.

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