IS THE GALACTIC DISK WELL MIXED?

M. G. EDMUNDS
Dept. of Applied Mathematics and Astronomy, University College, Cardiff, Great Britain

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Abstract. A consideration of the mixing processes for heavy elements in the interstellar medium suggests that the Galaxy is well-mixed locally. Inhomogeneities would be insufficient to explain the observed abundance spread of old disk stars, or to allow the theory of metal enhanced star formation to account for the paucity of metal poor dwarfs in the solar neighbourhood. Differential abundance effects during the formation of stars or clusters, or the existence of a radial abundance gradient may have to be invoked to explain the observations.

1. Introduction

Observational evidence suggesting that stars of a given age may differ from each other in chemical composition is examined in Section 2. It has been proposed that such a spread of abundances is due to chemical inhomogeneities in the interstellar medium (ISM) out of which the stars formed. In Section 3 we re-examine the mechanisms which cause or suppress the mixing up of elements in the Galactic disk. We conclude that the disk may be too well mixed on a local scale to explain all the observations unless additional abundance differentiation processes (Section 4) or a Galactic abundance gradient (Section 5) exist. In Section 6 two observational investigations to examine these processes are proposed.

2. Observational Evidence

It is generally assumed that the observed atmospheric compositions of 'normal' stars (i.e. stars which do not show atmospheric evidence of nucleosynthesis or element separation mechanisms occurring during their evolution) are the same as the composition of the ISM out of which they formed. Thus the metal abundance analysis of the spectra of stars of different ages will indicate the composition of the ISM at the times of stars' formation. Broad-band photometric investigation of F and G dwarfs can yield metal abundances. From the two-colour diagram for main sequence stars near the Sun, Dixon (1966) concluded that stars younger than about 3×10^9 years have a spread in metal abundance of $-0.3\leqslant[\mathrm{Fe/H}]\leqslant0.3$, where [Fe/H] is the logarithmic iron abundance relative to the Sun. For older, late-type stars he deduced $-0.1\leqslant[\mathrm{Fe/H}]\leqslant-0.3$. He inferred that the Galaxy was well mixed during an initial collapse, with an initial burst of star formation and that the Galaxy has been less well mixed since then. Powell (1972) used the ultraviolet excess of late F dwarfs as a metal abundance indicator and determined stellar ages by comparing their absolute magnitudes (calculated from observed magnitudes and parallax measurements) with theoretical

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evolutionary tracks. He showed a general increase of metal abundance from -0.5 a time 9×10^9 years ago to approximately solar now with a considerable spread $\sim \pm 0.25$ at any given time.

A similar investigation by Eggen (1964) also showed considerable spread among the metal abundances of stars within an age group. As noted by Talbot and Arnett (1973) (hereafter referred to as TA) he suggested spreads of ± 0.22, ± 0.35, ± 0.14 for stars of old, intermediate and young age groups. These investigations included quite a large number of stars, but the derived abundances must depend to some extent on atmospheric parameters, such as microturbulence, which were not explicitly taken into account. High dispersion spectral analysis can remove some of these uncertainties, but at the expense of smaller and probably biased samples. The spectrum scanner investigations of Spinrad and Taylor (1969) showed the existence of old stars significantly richer in metals than the Sun. Hearnshaw (1972), in an investigation ofnineteen old disks G-stars, found a range of metal abundances from metal poor -0.8 to supermetal rich $+0.4$ for stars formed 9×10^9 yr ago, a metal abundance variation by a factor of fifteen. As he quotes a typical age uncertainty of $\pm 1 \times 10^9$ yr for his stars, it is possible that the large abundance spread of these stars could be interpreted as just indicating a rapid change in the metal abundance (Z) of the ISM near the beginning of the Galaxy, if the given ages of the stars are systematically too young. Hearnshaw's younger stars have a smaller abundance spread -0.4 to $+0.2$. Gustafsson and Nissen (1972), from photoelectric narrow-band observations, find that the Hyades and Pleiades young clusters may differ in metal abundance by a factor 2, although other recent determinations of the Hyades metal abundance (Foy, 1974) may decrease the difference between these two clusters.

We suggest that the above investigations lead to the conclusion that there exists a spread in metal abundance of disk stars of any particular range of age, and that this spread may be smaller for recently formed stars than for older stars.

3. Mixing Mechanisms

The suggestion has been made that the spread of metal abundance in stars of a given age indicates that the ISM in the Galactic disk is not well-mixed, and that spatial variation of the ISM is just a statistical effect superimposed on a general variation of Z with time as supernova synthesis enriches the ISM. The formation before the Sun was formed, of stars richer in metals than the Sun is not itself surprising as studies of a simple closed system of gas and stars have shown that a peak can occur in the general variation of Z as time increases (Talbot and Arnett, 1971). It is the spread in values of Z at a given time which we consider here, and its implication for the model of galactic evolution proposed by TA. The important parameter is δZ, a measure of the typical difference in heavy element composition between points in the disk at a given time. A value of $\delta[\mathrm{Fe/H}] = 0.3$ would correspond to $\delta Z \sim 8 \times 10^{-3}$.

We are concerned only with the disk population, and shall not consider the halo.

The metal abundance of the disk is assumed to increase only by enrichment from supernova explosions. Recent studies of supernova remnants in the Galaxy (Ilovaisky and Lequeux, 1972) have suggested a supernova rate of $1/50\ \mathrm{yr}^{-1}$, and that each supernova (SN) expands to a radius of about 200 pc in 3×10^6 years before the supernova remnant expansion velocity becomes indistinguishable from random motions in the disk. As well as providing the source of metals, these explosions will act as a very effective mixing process (Reeves, 1972). If we assume a homogeneous model of the Galaxy as a disk of radius 12 kpc and thickness of the order of 200 pc, then each SN remnant will occupy a fractional volume $\sim 1/3600$ of the disk. If the SN rate has been constant over the age 1.2×10^{10} yr of the Galaxy (and it is unlikely to have increased with time) then at a point in the disk an average of at least 50 000 SN events will have contributed to the metal of the ISM at that point by the time of formation of stars which are now 9×10^9 yr old. This assumes that the remnants just fill their 200 pc radius with a uniform distribution of their synthesized metals. The probability that deviations of a factor of 15 required to explain Hearnshaw's observations occur in the number of local contributing events is extremely small. If n events contributed to give approximately solar abundance ($Z_\odot \simeq 10^{-2}$), then fluctuations of the order of $\delta Z \sim Z_\odot/\sqrt{n} \sim 4 \times 10^{-5}$ would be expected.

This argument assumes that star formation occurs randomly in time and space throughout the disk, which is certainly untrue. We must consider the interval between supernova explosion and subsequent formation of stars out of the metal-enriched ISM. By a density wave theory of the Galactic disk, we may expect an arm of the two arm spiral density-wave pattern to pass through the disk ISM every 2.8×10^8 yr at Sun's radius. As the density wave passes through the ISM star formation takes place in the leading shock (Roberts, 1969). The massive stars formed which delineate the spiral arm will evolve and explode on time scales (Iben, 1967) shorter than or of the order of the star passage time through the spiral arm. Indeed most of Galactic nucleosynthesis probably takes place within the spiral arms. Lower mass stars which may also give rise to some SN synthesis ($\sim 4\ M_\odot$) will only evolve on timescales of the order of the half-revolution time of the spiral pattern at the Sun ($\sim 2.8 \times 10^8$ yr). Roberts (1972) suggests that outside the Sun's radius there may be evidence for some four-arm spiral structure, which will decrease the intershock time at those radii by half. The star formation caused in these shocks is patchy, and it seems likely that most, if not all, of the massive stars which will subsequently give SN synthesis are formed is OB association. Reeves (1972) pointed out that heavy element synthesis is thus localized because the massive stars will explode on time scales shorter than the dissolution lifetime of the cluster and pour all their metals into the same volume. Deducing from Blaauw (1964) a model of an OB association of linear dimensions 60 pc, total mass $200\ M_\odot$ containing 15 O–B2 stars, then if each OB star gives $6\ M_\odot$ of metals in SN explosion about $90\ M_\odot$ of metals will be poured into about $3 \times 10^7\ \mathrm{pc}^3$. From momentum and energy considerations (Tayler, 1971; Reeves, 1972; TA) a single SN gives $\delta Z \sim 3 \times 10^{-4}$ between inside and outside the remnant, thus with all SN metals from

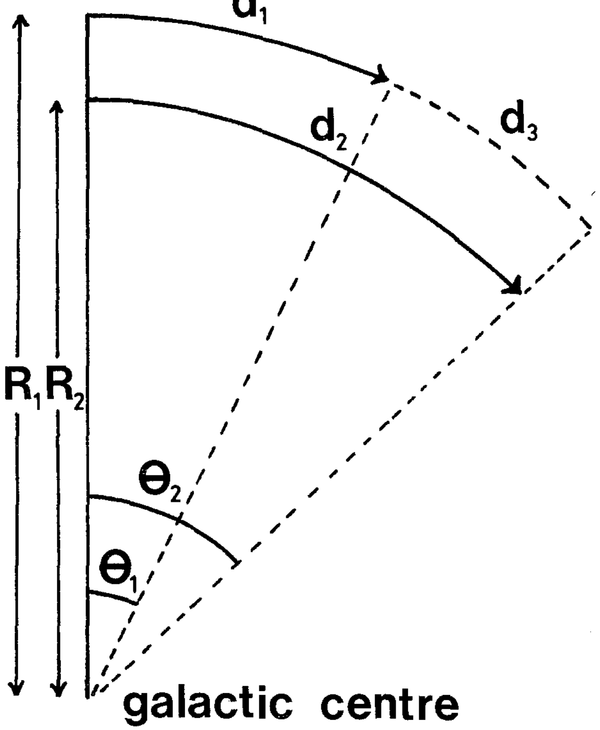

Fig. 1. Geometry of galactic rotational shear.

OB association into the same volume we expect $\delta Z \sim 4 \times 10^{-3}$.

The crucial question is whether this inhomogeneity will persist until star formation takes place again. Turbulent transport by eddies in the ISM give a mixing length (TA) in τ years of

$$L \sim 1.8 \times 10^{-2} \sqrt{\tau}\ \text{pc}. \tag{1}$$

If $\tau \sim 2.8 \times 10^8$ yr then $L \sim 300$ pc, and hence of the order of the volume the SN explosions will themselves have mixed. If $\tau \sim 1.4 \times 10^8$ yr (four-arm pattern), $L \sim 220$ pc. As diffusive mixing takes place, Galactic rotation will shear the mixing volume into an arc about the galactic centre. In Figure 1, if the rotational velocity at R_1 is V_1, at R_2 is V_2, then after time t

$$V_1 t = d_1 = R_1 \theta_1; \qquad V_2 t = d_2 = R_2 \theta_2$$

Thus

$$d_3 = R_1(\theta_2 - \theta_1) = \left(\frac{R_1}{R_2} V_2 - V_1\right) t.$$

At the solar radius $\mathrm{d}V/\mathrm{d}R \simeq 5$ km s^{-1} kpc^{-1} (Allen, 1973). Thus for a radial mixing of 0.3 kpc in 2.8×10^8 yr,

$$V(10\ \text{kpc}) \simeq 250\ \text{pm s}^{-1}, \qquad V(9.7\ \text{kpc}) \simeq 248.5\ \text{km s}^{-1}$$

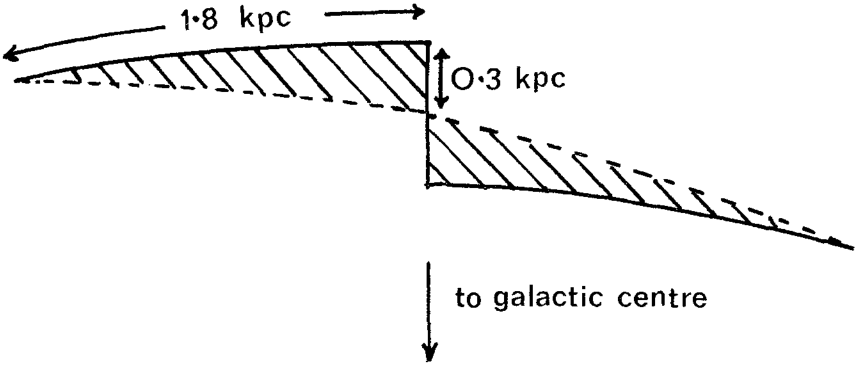

Fig. 2. Volume mixed between shocks at solar radius.

and $d_3 \sim 1.8$ kpc. As this shearing takes place, the enriched gas from the association will be mixed outwards by turbulence and low mass SN into triangular prism of volume in each direction, as shown in Figure 2. A total volume of approximately $1.8 \times 0.3 \times 0.2$ kpc$^3 = 1.1 \times 10^8$ pc^3 will be mixed. Blaauw (1964) estimates that there are 11 OB associations within 1000 pc of the Sun, implying (on a 200 pc thick disk model) a space density of 1 association per 6×10^7 pc^3, hence perhaps two associations will contribute a total of 180 $M_\odot$ of metals into 0.11 kpc^3 of gas. Now using a gas density near the plane of 0.018 $M_\odot$ pc^{-1} (Allen, 1973) implies a mixed mass of 1.9×10^6 $M_\odot$, and inhomogeneities will be of order $\delta Z \sim 9 \times 10^{-5}$ by the time of the next star-forming shock. The longer-lived stars of lower mass than the most massive SN stars will have time to disperse away from their places of formation before they explode, and these random SN explosions will also help to mix up the ISM. TA have suggested that the mixing between shocks will be severely inhibited by the trapping of material in magnetic wells formed by instabilities in the galactic magnetic field/gas system. There seems to be much evidence, however, that the galactic magnetic field is best accounted for by a stochastic model (Jokipii and Parker, 1969; Jokipii *et al.*, 1969) with a correlation length λ of about 150 pc for ISM fluctuations. This implies a typical lifetime for structure in the field of $\tau \sim \lambda / V_t$, where V_t is the ISM turbulent velocity. With $V_t \sim 10$ km s^{-1}, then $\tau \sim 1.5 \times 10^7$ yr, much shorter than the intershock mixing time. We conclude that the magnetic field structure will vary too quickly to affect the mixing process.

Trapping of elements might also occur in the magnetic fields of individual SN remnants. The magnitude of the fields generated in a SN remnant containing a pulsar may be estimated from the model of Goldreich and Julian (1969). The torroidal field in the boundary zone (about 90% of radius of SN cavity) at radius r pc is given approximately for a pulsar of one solar mass, period p, age τ, by

$$B_t \sim \frac{6 \times 10^{-5} \tau^{-1/2}}{pr}.$$

If we put $p = 0.3$ for a remnant of age 10^6 yr, radius 200 pc gives $B_t \sim 3 \times 10^{-9}$ G.

This is much less than the interstellar field, and hence no trapping of elements within the remnant will occur. No reliable estimate can yet be made of the fields outside more highly-collapsed objects.

We conclude from the above arguments that the interstellar medium is fairly well mixed, and that if star formation and subsequent metal synthesis occurs in a density wave shock then a spread of only $\delta Z \sim 10^{-4}$ would be expected by the time of passage of the next shock.

TA proposed a model of galactic evolution in which the rate of star formation depends on the local metalicity of the ISM. The model is attractive because it can explain the paucity of metal-poor dwarfs in the solar neighbourhood, whilst a simple enrichment model would predict many more than are observed. However, even with the limiting case of extreme enhancement of star formation by metals, in order to explain the observed number of metal-poor dwarfs a value for δZ of at least 8×10^{-3} is required, much larger than our mixing estimate. We conclude that additional mechanisms are needed to explain the observed spread of metal abundances of stars of the same age and the spread in metal abundances in the ISM which is required if the metal enhanced star formation model is to work.

4. Localized Abundance Differentiation Mechanisms

In the previous section we have assumed that all star formation takes place as the density wave shock passes through the ISM, and that the ISM then mixes until the next shock passes. Although OB associations account for the formation of massive stars, the places of formation of lower mass stars are not well known. The observed mass function of OB associations has a marked deviation from the usual initial mass function towards massive stars. Low mass stars may form in OB association and subsequently relax out (Biermann, 1974). Enhancement of metal abundance could occur if star formation were triggered in the expanding enriched material of a SN shell. Tayler (1971) suggests that such condensation is unlikely to occur until the expansion has slowed to the typical turbulent ISM velocities and by this time $\delta Z \sim 3 \times 10^{-4}$. Schwartz *et al.* (1972) and Stein *et al.* (1972) have suggested that protostellar condensations could be induced by sudden heating of the ISM by, for example, a SN explosion. Could enriched low mass stars be formed in this way in $\delta Z \sim 4 \times 10^{-3}$ OB association gas and subsequently relax out? If the massive stars are about $20\,M_\odot$, relative velocities about 5 km s^{-1}, and the distance between the stars is about D pc, then from Chandrasekhar (1942; Equation 2.380) the relaxation time

$$\langle \overline{T}_E \rangle \simeq \frac{4.4 \times 10^8\, D^3}{2.46 + \log_{10} D}\ \text{yr}.$$

If we assume that an OB association contains perhaps 200 stars, and expands linearly to 60 pc in 10^7 yr, then after t yr,

$$D \sim \frac{60t}{(200)^{1/3}10^7} \sim 10^{-6}t \text{ pc}.$$

Putting $t = 10^6$ yr, when the massive SN will begin to blow up, we find that $\langle \bar{T}_E \rangle \sim 1.8 \times 10^8$ yr. In order for the low mass stars to have time to relax out of the association and hence explain the observed luminosity function, the formation of low mass stars must occur during earlier denser phases of the association (when $\bar{T}_E$ is much shorter) and hence *before* the explosions of the massive stars enrich the ISM. The δZ of these low mass stars will not be enhanced.

There is evidence of protracted star formation in subclusters in OB associations. Typically (from Blaauw, 1964) two subclusters of stars with centres about 30 pc apart may have a difference in age of 4×10^6 yr – sufficient for the SN of one subcluster to have enriched the material out of which the second group formed, and prehaps allowing $\delta Z \sim 4 \times 10^{-3}$ between the low mass stars of the two subclusters. If low mass stars are formed outside OB associations, then the inhomogeneities ($\delta Z \sim 8 \times 10^{-3}$) required for metal enhanced star formation theory will only be effective if low mass star formation occurs without shock inducement in the enriched gas from an OB association after the association has lost its identity, but before much mixing takes place. An additional constraint would be that such star formation would have to contribute only low mass stars, because all massive star formation can be accounted for in OB associations.

We suggest that effects occurring during the actual process of star formation may produce some of the spread in metal abundances. The influence of metal abundance on the initial mass spectrum in star formation could be important. If the whole spectrum shifted towards higher masses by increased metal abundance then relatively more metal producing SN would occur and metal abundance perturbations would grow, but this would have to be an extremely strong effect if it were not to be smoothed out by mixing. But as yet there is no star formation theory which can predict even which way the mass spectrum will shift with increasing metal abundance.

The assumption that the atmospheric composition of stars reflects the ISM out of which they formed may require revision. Edmunds and Wickramasinghe (1974a, b) have shown that transport of metallic grains in the envelopes of collapsing protostars could produce massive stars of metal abundance lower than the medium out of which they formed, and hence that stars of various compositions could form in the same association. The dynamics of metal-enriched gas and dust within star-forming association requires detailed study.

5. Galactic Abundance Gradient

Large scale radial abundance gradients have been observed in nearby galaxies (Searle, 1971) and it is quite possible that a similar gradient could exist in our own Galaxy. From Equation (1), the turbulent mixing time from the centre of the Galaxy to the Sun is 3×10^{11} yr, longer than the age of the Galaxy. There may be some radial gas streaming (Roberts, 1972) but this will only be on a scale of 4% of the radius per revolution of the density wave pattern through the disk, and hence a radial abundance gradient could persist over a galactic lifetime. Grenon (1973) has suggested that the spread in metal abundance of stars observed at the solar radius could be due to their having been formed at different radii (and hence different Z), and whose motions have subsequently brought them into the solar neighbourhood. We would then expect young stars, and low velocity stars of similar ages, in the solar neighbourhood to have a smaller range of abundances than old high velocity stars. Extremely old stars ($\sim 1.2 \times 10^{10}$ yr) might have a large range of abundances due to initial inhomogeneities. It is not possible to determine with any accuracy the places of formation of stars older than 5×10^{8} yr from proper motions and age calculations (Strömgren, 1967) but some support is given to the idea of migration from radii of different Z by the observation that stars with high velocities have a larger range of abundances than low velocity stars (Williams, 1971).

The abundance gradient could have been set up in the initial collapse of the Galaxy, and simplified models (Larson, 1974) suggest that even the paucity of metal-poor dwarfs may be explained with such a model. Another mechanism which may generate, or enhance, an abundance gradient is the 'piling up' of density wave energy against the inner Lindblad resonance ring resulting in stronger shocks (Lin, 1971), and hence more star formation and metal synthesis, towards the centre of the Galaxy. Some support for this mechanism is given by the observation of increased number density of H II regions (and hence young, massive stars) towards the centre, despite little increase in H I.

6. Observational Tests

If abundance differentiation mechanisms exist in star formation as suggested in Section 4, then an accurate high-dispersion analysis of a star cluster should reveal abundance differences between apparently normal stars in the cluster. Correlation of such differences with mass and position in the cluster, particularly relative to gas and dust, would give clues to the differentiation processes. If such mechanisms are not important, and a large part of the abundance spread of stars is due to stellar migration within a galactic abundance gradient, as suggested in Section 5, then an accurate analysis of all disk stars formed recently in the solar neighbourhood should reveal very little abundance spread.

7. Conclusion

We have shown that the galactic disk is well mixed locally, and that inhomogeneities in metal abundance of the ISM are probably too small to explain the observed spread in abundance of stars of a given age or to allow metal enhanced star formation to explain the paucity of metal poor dwarfs. We suggest that either differentiation processes within star or cluster formation, or the existence of a large-scale radial abundance gradient, rather than poor mixing, are required to explain the observations.

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Note added in proof. R. J. Talbot (*Astrophys. J.* **189**, 209, 1974) has recently discussed the mechanism of metal-enhanced star formation in more detail than TA. The required δZ of 1.5×10^{-3} to 3.0×10^{-3} is somewhat less than before, but still much greater than implied by our mixing estimates unless mechanisms like those of Section 4 above are invoked. B. E. J. Pagel (*Chemical History of the Galaxy*, Intl. Centre for Theor. Phys. Trieste. Internal Report IC/73/169, 1973) has shown that the simple Larson (1974) inhomogeneous collapse models do not satisfactorily account for the paucity of metal-poor dwarfs in the solar neighbourhood.

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