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THE DISPERSAL OF IRON THROUGH THE INTERSTELLAR MEDIUM[1]

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ABSTRACT

Simple calculations on the dispersal of iron through the interstellar medium (ISM) indicate that cloud motions may be the most important mechanism for this dispersal, whereas turbulence in the intercloud gas and, in a three-phase ISM, supernova shocks probably play a lesser role. The calculations raise some doubts as to the importance of chimneys for mixing on a Galactic scale, though there is insufficient observational data to draw more than tentative conclusions. The distance over which iron produced by a supernova in the local Galactic disk is mixed over one recycling time of the ISM is found to be between about 0.5 and 2.0 kpc, consistent with the chemical homogeneity of star clusters and the observed gradient in [Fe/H]. These results are summarized in Table 2.

Subject headings: ISM: abundances — ISM: kinematics and dynamics — supernovae: general

1. INTRODUCTION

Heavy elements are produced in stars and recycled through the interstellar medium (ISM) to later generations of stars. The sources of heavy elements are thus very localized on a galactic scale, yet the observed distribution in stars is quite uniform. An analysis of the mechanisms involved in this mixing of the elements through the interstellar medium can provide insight in many fields of astronomy. Among other applications chemical evolution models generally assume uniform mixing, or some kind of radial mass flow, and the extent of mixing provides some useful information for models of Galactic formation. For example, globular clusters are chemically uniform, thus the size of the clouds from which they were formed can be constrained by the distance over which mixing could occur (assuming that the stars were all formed at the same time).

In their ground-breaking discussion of the "chimney model" Norman & Ikeuchi (1989, hereafter NI) imply that the cycling of matter through the Galactic halo will play a role in the transport of the heavy elements through the Galaxy, but they present no estimate of the importance of this effect. Indeed no calculations on the subject of the dispersal of heavy elements through the Galaxy have been published. We hope to address this situation by examining the efficiency of mixing of heavy elements through different mechanisms, to attempt to determine which are most important.

To keep this calculation simple we make several assumptions. We take the root mean square (rms) distance traveled by the iron atoms produced in a supernova in one recycling time of the ISM as a measure of the efficiency of mixing. We choose iron as an example for several reasons: first, because the sites of iron production are relatively well known (Timnes 1991 calculates that at the present time 65% of iron is formed in Type I supernovae); second, because, unlike Type II supernovae, these sites are not correlated; and third, because iron is often used to trace the abundance of all heavy elements. Although most Type I supernovae (SNI) occur in the Galactic halo (Heiles 1987) we consider only those that take place in the disk; we will address the role of the halo in § 5. To compare mixing in different phases of the ISM we assume that the time spent in each phase is proportional to the total mass of gas in that phase. We restrict our calculation to the determination of the rms mixing distance for the ISM at the present epoch and in the solar neighborhood in the absence of magnetic fields. We do not consider the motion associated with the expansion of supernova remnants, nor the mixing which must take place during such an event, since on the distance scales we are considering these effects are probably quite small. In particular the largest observed supernova remnants are all smaller than several hundred parsecs (Dickey & Lockman 1990), and the larger structures probably result from multiple supernovae.

We use the term recycling time to refer to the time constant for the incorporation of interstellar material into new stars. This can be calculated from the star formation rate and the surface density of Galactic gas. Typical numbers at the solar radius are 5 $M_\odot$ $\mathrm{Gyr^{-1}\ pc^{-2}}$ for the star formation rate (Mezger 1988), and 13 $M_\odot$ $\mathrm{pc^{-2}}$ for the density (Kulkarni & Heiles 1987; Kuijken & Gilmore 1989). This gives a recycling time of 2.6 Gyr; using different numbers it can range from 1 to 4 Gyr. Salpeter (1977) gives an often used time of 2 Gyr, through he uses a lower gas density than more recent estimates.

In our analysis we will use the nomenclature introduced by McKee & Ostriker (1977, MO) to describe the different phases of the ISM. First we consider dispersal by cloud motions in the cold neutral medium (CNM), including molecular and atomic clouds. Second we attempt to quantify the effect of turbulence in the pervasive medium (warm neutral and warm ionized media, WNM, WIM), and third we consider dispersion through the hot ionized medium (HIM) of the three-phase model. Finally we will briefly consider mixing through the halo, concentrating on the chimney model.

We have assumed a range of values for various Galactic parameters; Table 1 lists these ranges. For each parameter we

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TABLE 1[a]

PARAMETERS USED IN CALCULATIONS

Parameter	Symbol	Value
Recycling time for matter in the ISM	t_{rec}	1–4 Gyr
Standard cloud collision time	$\tau_{H\,I}$	10 Myr
Standard cloud velocity	$v_{H\,I}$	10 km s^{-1}
Mass filling factor of H I clouds	$f_{H\,I}$	0.4
Molecular cloud lifetime	τ_{MC}	7–13 Myr
Molecular cloud velocity	v_{MC}	5–14 km s^{-1}
Mass filling factor of molecular clouds	f_{MC}	0.2–0.5
Turbulent velocity	v_{turb}	10 km s^{-1}
Turbulent correlation length	l_{turb}	80 pc
Mass filling factor of diffuse media	f_{diff}	0.1–0.4
Type I supernova rate	r_{SN}	0.004–0.029 pc^{-2} Gyr^{-1}
Mass filling factor of HIM	f_{HIM}	0.001

[a] For references see text.

used the appropriate extreme number to calculate maximum and minimum mixing distances; our results are summarized in Table 2.

2. CLOUD MOTIONS IN THE COLD NEUTRAL MEDIUM

The problem of modeling the formation and dynamics of clouds, and in particular the formation and destruction of star-forming giant molecular clouds, is not well understood. Thus it is difficult to determine accurately the rms distance that an iron atom could travel in such clouds. A simplifying assumption is to consider two limiting cases of cloud interactions, namely that all cloud interactions result in isotropic scattering, or in no change in the direction of motion of either cloud. Neither of these assumptions is completely realistic, but the best description presumably lies somewhere between the two.

First we assume that every time a "standard" H I cloud interacts with another it is scattered isotropically, while molecular clouds travel in straight lines until they are destroyed. Since star formation tends to blow giant molecular clouds apart relatively quickly, this second assumption seems to be safe. We assume that the debris from such an event is formed into atomic clouds, again on a short time scale. The rms distance traveled by a cloud, and thus by a heavy atom under such assumptions is the superposition of two random walk processes, one in molecular clouds, and one in atomic clouds. The rms distance traveled in each process is then

$$R_i = (\tfrac{2}{3} v_i^2 \tau_i t_i)^{1/2} , \qquad (1)$$

where v_i is the mean (three-dimensional) velocity in each phase of the gas, τ_i is the time between scattering events, and t_i is the total time spent in that same phase of the gas. We assume that these times are proportional to the mass of the phase and to the total recycling time, i.e.,

$$t_i = \frac{m_i}{m} t_{rec} = f_i t_{rec} , \qquad (2)$$

where t_{rec} is the recycling time of interstellar gas, m_i is the total mass of the phase in question, m is the total mass of the ISM, and we introduce f_i as the mass filling factor of that same phase.

For these parameters we adopt the following numerical values: from Spitzer (1978), the average collision time for H I clouds ($t_{H\,I}$) is 10 Myr, and their mean velocity ($v_{H\,I}$) is 10 km s^{-1}, which corresponds to about 10 pc Myr^{-1}. The molecular clouds have velocities (v_{MC}) from 5 km s^{-1} (Clemens 1985) to 14 km s^{-1} when streaming motions are included (Stark & Brand 1989). The importance of streaming to our analysis is not entirely clear, so the above numbers have been taken as upper and lower limits. The percentage of the mass of the ISM in molecular clouds (f_{MC}) is open to debate, with estimates varying from 20% (McKee 1990) to 50% (Scoville & Sanders 1987), while most authors believe that H I clouds constitute about 40% of the mass of the ISM ($f_{H\,I}$; e.g., Draine 1990). To a large extent such ratios are a function of Galactic radius and scale height, so we have taken the appropriate numbers as upper and lower limits. The last parameter needed is the lifetime of giant molecular clouds. A typical free-fall time for such a cloud is about 2 Myr, and star formation starts shortly after the formation of the cloud (Blitz 1990). Observationally it has been estimated that nearly all the mass of the cloud has been blown off 5 Myr after the onset of star formation (Leisawitz 1985; Leisawitz, Bash, & Thaddeus 1989). Thus the travel time in molecular clouds (τ_{MC}) is taken to be between 7 and 13 Myr. A superposition of random walks in molecular and H I clouds gives rms travel distances between 0.5 and 2.1 kpc, if the diffuse medium contains between 10% (Draine 1990) and 40% (McKee 1990) of the mass of the ISM.

The other limiting case we consider is that only the onset of star formation alters the direction of travel of "standard" clouds, i.e., H I clouds travel in straight lines until they are formed into molecular clouds. To further simplify the calculation we assume that all molecular gas is located in star-forming molecular clouds. Then both molecular and atomic clouds travel in straight lines until being blown apart by star formation, in the case of molecular clouds, or incorporated

TABLE 2

RMS DISTANCE TRAVELED BY IRON IN DIFFERENT PHASES OF THE ISM IN ONE RECYCLING TIME

Mechanism	R_{min} (kpc)[a]	R_{max} (kpc)[b]
Clouds	0.5	2.1
Turbulence (in t_{rec})	0.7	1.4
Reduced for mass	0.23	0.92
HIM	5.1	11
Reduced for mass	0.16	0.35

[a] Distance traveled with Galactic parameters chosen to minimize distance.

[b] Distance traveled with Galactic parameters chosen to maximize distance.

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into molecular clouds for atomic clouds. The distance traveled before such an event is considered to be one step in a random walk, and the total distance traveled in each phase in one recycling time can be calculated from equation (1). All the necessary parameters are given above, except for the time in each step for atomic clouds ($\tau_{\rm H\,I}$), i.e., the time until an H I cloud is incorporated into a molecular cloud. This can be calculated by considering the number of steps taken in the random walk. Since each step in H I clouds ends with the cloud being incorporated into a molecular cloud, and each step in a molecular clouds ends with the cloud being dissociated into atomic clouds, the number of steps taken in each phase must be equal. This number must be

$$N = \frac{t_{\rm MC}}{\tau_{\rm MC}} = \frac{t_{\rm H\,I}}{\tau_{\rm H\,I}} , \quad (3)$$

using the above notation. Then from equation (2)

$$\frac{t_{\rm rec} f_{\rm MC}}{\tau_{\rm MC}} = \frac{t_{\rm rec} f_{\rm H\,I}}{\tau_{\rm H\,I}} , \quad (4)$$

and

$$\tau_{\rm H\,I} = \frac{f_{\rm H\,I}}{f_{\rm MC}} \tau_{\rm MC} . \quad (5)$$

One potential problem with this treatment is that it does not take into account small molecular clouds (i.e., those which are too small for star formation). It is certainly possible that when larger star-forming clouds are blown apart much of the debris remains in molecular form, in smaller clouds. However, the role of small molecular clouds in our calculation is presumably similar to that of atomic clouds, if they have about the same velocity distribution. One way of estimating the effect of these clouds would be to change the filling factors for atomic and molecular gas (we used a range of 0.2 to 0.5 for molecular clouds). We do not believe this will significantly change our results because most molecular mass is in large clouds. In particular Scoville (1990) estimates that 50% is in clouds larger than $4 \times 10^5\ M_\odot$, so the mass of these small molecular clouds is probably not very significant.

Using formula (5) to find $\tau_{\rm H\,I}$ and using the above values for all the other parameters, we find rms travel distances of between 0.5 and 2.1 kpc from equation (1). The fact that the results of the two extreme models agree so well is due to the fact that the velocities for molecular and atomic clouds were chosen to be quite similar, and that equation (5) results in values of $\tau_{\rm HI}$ which are very similar to the intercloud collision times of Spitzer (1978).

To verify the consistency of the chosen parameters we can use them to calculate the efficiency of star formation in molecular clouds. This efficiency (ϵ) can be defined as the mass fraction of a molecular cloud that is formed into stars over the lifetime of the molecular cloud. Then any given atom should go through $1/\epsilon$ clouds in one recycling time, so the percentage of interstellar mass in molecular clouds should be equal to the ratio of $1/\epsilon$ times the time spent in one molecular cloud ($\tau_{\rm MC}$) and the recycling time of the gas. That is,

$$f_{\rm MC} = \frac{\tau_{\rm MC}\, 1/\epsilon}{t_{\rm rec}} . \quad (6)$$

From equation (6) the assumed values give ϵ between 0.7% and 1.4%, but choosing some maximum and some minimum values can give up to 5%. A typical efficiency determined from observations is 2% (Myers et al. 1986). Thus the assumed parameters are consistent with these results.

3. TURBULENT DISPERSAL IN THE PERVASIVE DIFFUSE MEDIUM

Turbulence in the diffuse intercloud medium may also be important for the dispersion of heavy elements through the Galaxy. The rms distance traveled by a fluid element under turbulent conditions is

$$R_{\rm rms} = (\tfrac{2}{3} v_{\rm turb}\, l_{\rm turb}\, t_i)^{1/2} , \quad (7)$$

where $v_{\rm turb}$ is the turbulent velocity, and $l_{\rm turb}$ is the velocity correlation distance for the motion. Unfortunately very little is known about the dominant state of the diffuse medium; it may be the HIM of the three-phase model or the WNM or WIM of the two-phase model. Observations of the relevant velocity distributions and correlation distances within the medium would clearly be very helpful here. Despite the lack of data we will attempt to estimate the possible importance of this mode of dispersion. If the pervasive medium is really the HIM supported by supernovae, then supernovae can be expected to dominate the turbulence in the diffuse medium. We will deal with this in the next section of this paper. However, if the pervasive medium is the warm medium of the two-phase model then the turbulent motions may be similar to the cloud motions in the cold medium, for which a correlation length ($l_{\rm turb}$) of about 80 pc has been estimated (Kaplan & Pikelner 1970). This implies that a fluid element in the diffuse medium would travel an rms distance of about 0.7 to 1.4 kpc over one recycling time. However, it should be noted that the warm diffuse medium contains only about 10% (Draine 1990) to 40% (McKee 1990) of the total mass of the ISM, so that from equations (2) and (7) the actual rms travel distance in the diffuse medium should be reduced to between 0.2 and 0.9 kpc. Thus while the diffuse medium may have at least as uniform a chemical composition as the other phases, it probably does not play such a large role in the dispersion of heavy elements. However, all such conclusions rest on the questionable assumption that turbulence in the diffuse medium is similar to the turbulence observed in clouds; for concrete conclusions better observations are required.

4. DISPERSAL THROUGH SUPERNOVAE IN A HOT IONIZED MEDIUM

An alternative to a pervasive warm medium with turbulence similar to cloud motions is a pervasive hot medium dominated by supernova explosions. To estimate the effects this might have we adopt the model proposed by MO, in which the ISM is continually swept by shocks from supernova remnants. They locate the transition of such a shock from adiabatic to isothermal expansion at a radius of 182 pc at a time of 0.79 Myr. If the SNI rate is 0.006 $\rm pc^{-2}\ Gyr^{-1}$ (van den Bergh 1991), about 0.5 SNI events are expected in a region of this size during this time interval, roughly consistent with an ISM sustained by these shocks. Type II SNs are much more strongly correlated in space and time; to simplify the calculation we have chosen to ignore them since they should produce only a small number of superbubbles, and they produce little iron. Admittedly they will have very large local effects on mixing wherever a superbubble is produced.

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From the SNI calculation it seems reasonable to assume that the dispersion of iron through the HIM would be dominated by the motion of supernova shocks. We make the further assumption that this motion can be modeled as a random walk process, each step in the walk involving the straight motion of a shock front for a distance such that the area enclosed and the time elapsed are such that one supernova is expected. We then alter equation (1) such that

$$R_i = \left(\frac{2}{3}\frac{l^2}{\tau_i}t_i\right)^{1/2}, \quad (8)$$

with the same notation as equation (1), but with l the average distance traveled in each step. As explained above we find these parameters from

$$\tau\pi l^2 = \frac{1}{r_{\mathrm{SN}}}, \quad (9)$$

where r_{SN} is the areal SNI rate, together with the time dependence of the shock velocity given by MO. The Galactic SNI rate is subject to some debate; we use extreme values of 0.029 pc^{-2} Gyr^{-1} (Tammann 1982), and 0.004 pc^{-2} Gyr^{-1} (van den Bergh 1991). These values give a predicted rms travel distance in the HIM of 0.16 to 0.35 kpc. These distances are so small because t_i for the HIM is very small (in the MO model its mass can be calculated to be only about 0.1% of interstellar mass). Thus while the HIM may be chemically uniform over very large distances (5–11 kpc), its low mass implies that a chemically uniform HIM may not have much effect on the bulk distribution of heavy elements.

5. THE ROLE OF THE GALACTIC HALO

As noted above, one difficulty with the arguments we have made about the motion of iron in the disk is that most iron is produced in Type Ia supernovae, of which 62% take place in the Galactic halo (Heiles 1987). This fact will clearly change our results, but it is hard to estimate the importance of its effects given the state of our knowledge of the velocity distribution of gas in the halo. However, we can consider three possible scenarios.

First, if there is a Galactic wind as suggested by many authors (e.g., Volk, Breitschwerdt, & McKenzie 1989) then the matter in the halo cannot play a large role in determining the heavy-element abundance of the disk. In this case most iron created in the halo would be blown into the intergalactic medium. Second, if the mixing in the halo is not as large as in the disk, then our analysis is valid, since the iron will fall approximately vertically into the disk. Finally if the mixing in the halo is more efficient than in the disk, then our analysis is indeed inappropriate. In this case the iron would be quite well mixed before entering the disk, and disk processes would be secondary in importance to those in the halo. However, such mixing cannot be so effective as to destroy the gradient in the observed Galactic iron abundance, implying that the distance must be less than about 5 kpc.

Norman & Ikeuchi (1989) imply that chimneys may play an important role in the dispersion of heavy elements. We believe that there may be some doubt about this question. In particular NI estimate that the total mass outflow rate in chimneys for the Galaxy is only about 0.3 to 3.0 $M_\odot$ yr^{-1} which is smaller than most estimates of the total rate of star formation in the Galaxy ($\approx$3–5 $M_\odot$ yr^{-1}; Mezger 1988), therefore most of the ISM is likely to be processed into stars before being ejected into the halo via chimneys. If in the most favorable case each iron atom is ejected into the halo once before being incorporated into a star, then we can state that to compete with cloud motions the travel distance in the halo must be of the order of a kiloparsec. For a halo residence time of 20–30 Myr (NI), this would require the gas to be moving at about 50 km s^{-1}. The calculations of NI find that mass is expelled to the halo with a velocity of about 200 km s^{-1}, so it is certainly possible that the average component of the velocity in the plane of the disk could remain 50 km s^{-1} during residence in the halo. Unfortunately, as noted above, very little is known about the velocity distribution of gas in the halo. However it is important to note that 62% of all SNIa events take place in the halo, and so most iron is released to the ISM in the halo. Thus if there is very efficient mixing in the halo, most iron could take advantage of it without invoking a chimney model. However, it is likely that most iron atoms are not even ejected once into the halo by a chimney, so it appears that chimneys may not play an important role in the dispersal of iron.

6. DISCUSSION

Our results can be summarized as follows:

1. We used two extreme models of cloud interactions; using the known velocities and collision times, along with the percentage of the mass of the medium in molecular clouds we find an rms distance for distribution by clouds of between 0.5 and 2.1 kpc.

2. Assuming that turbulence in the pervasive medium has the same characteristics as the turbulence observed in cold matter, we find an rms distance in this medium of about 0.2 to 0.9 kpc. More observations would be very useful in determining the importance of such turbulence.

3. Assuming that dispersion through a three-phase type HIM would be dominated by supernova shocks and using some results from MO we find that for the expected time spent in the HIM an rms distance would be from 0.2 to 0.4 kpc.

4. We note that at the present state of knowledge of the velocities of gas in the halo we cannot determine the importance it may play. However, using some of NI's results we find that there should be some doubt as to the importance of chimneys in mixing. Again better observations could help to clarify the importance of the Galactic halo in the dispersion of heavy elements, and in particular the role of chimneys.

To check the consistency of these results it would be helpful to know what sort of distance scale should be expected for mixing. One measurement which gives such a distance scale is the radial gradient of iron. It is well known that this gradient is about -0.05 dex kpc^{-1} (e.g., Pagel & Edmunds 1981), and if we assume that all iron is produced in SNIa events then the distribution of production sites should be the same as the density distribution of old disk stars. These have a radial scale length of 3.5–5.5 kpc (Freeman 1987). The calculated dispersion through the ISM is thus small enough to allow the persistence of the gradient, but large enough to play some role in smoothing out local inhomogeneities smaller than about 1 kpc. However the time scale we are considering is quite large (1 Gyr) so such inhomogeneities could persist for some time. Since the gradient is not well understood we cannot draw extensive conclusions; we can only note that our results are consistent with present knowledge.

Another measurement to which these results could be applied is the small abundance variations within globular clus-

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ters. These clusters are observed to be quite uniform (Searle & Zinn 1978) implying that the material out of which they formed was well mixed. Given their age it may be somewhat naïve to assume that mixing at that time was the same as in the present epoch, but the distance over which they are usually assumed to collapse is about a kiloparsec, which is consistent with our calculations.

Thus we find that dispersion through the diffuse medium is probably less important for the dispersion of heavy elements than the motion of clouds, though this conclusion depends on the nature of turbulence in the diffuse medium. We cannot draw even tentative conclusions about the potential role of chimneys, or of other mechanisms involving the expulsion of matter into the halo, most importantly fountains (e.g., Kahn 1989) and the "dust fountain" (Ferrara et al. 1989), without more knowledge of the halo; while it is certainly possible that chimneys are critical for mixing, it is equally possible that their role is much less than that of cloud motions. Finally it is important to note that we have ignored several important effects, in particular Galactic magnetic fields and rotation.

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