A Massive Star Odyssey, from Main Sequence to Supernova
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Dispersal of massive star products and consequences for galactic chemical evolution

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Abstract. The processes that disperse the products of massive stars from their birth sites play a fundamental role in determining the observed abundances. I discuss parameterizations for element dispersal and their roles in chemical evolution, with an emphasis on understanding present-day dispersion and homogeneity in metallicity. Turbulence dominates mixing processes, with characteristic timescales of order 10^8 yr, implying significant dilution of metals into the ISM. This permits a rough estimate of the metallicity distribution function of enrichment events. Many systems, including the Milky Way and nearby galaxies, show metallicity dispersions that as yet appear consistent with pure inhomogeneous evolution. There are also systems like I Zw 18 that show strong homogenization, perhaps tied to small galaxy size, high star formation rate, and/or superwinds.

1. Introduction

The dispersal of the nucleosynthetic products of massive stars plays a fundamental role in galactic chemical evolution. Our ability to decipher the chemical signatures of star formation history depend upon understanding the dispersal processes. The growing database and improving accuracy in elemental abundance determinations increasingly is revealing the magnitude of abundance dispersions, and setting limits on uniformity. It is apparent that the magnitude of these dispersions results directly from the balance between interstellar transport processes and the timescale for global star formation. This field of study is presently still in its infancy, but I will discuss here some of our rudimentary knowledge.

Dispersal of newly-synthesized elements takes place on three levels: **1.** Local **mixing** with the ambient interstellar medium (ISM); **2.** Global **homogenization** of a system or subsystem; **3. Outflow / inflow** of metals from the considered system. The local mixing processes describe the immediate dispersal of elements associated with individual star-forming regions into areas of roughly uniform metallicity. Homogenization of the system then describes the mixing of these individual patches toward globally uniform abundances. Finally, outflows and inflows consider the transport of metals beyond the system altogether. Other presentations in this volume (e.g., Strickland; Matteucci) consider the last; here, I will consider only the first two processes, which apply only within a given system.

2. The simplest models

Rudimentary representations of mixing essentially correspond to models for inhomogeneous chemical evolution. In the very simplest model, the metallicity of a system is considered to be built up by identical individual patches of contamination representing, for example, individual supernova remnants (SNRs). If these patches are all uniform in size and metallicity, then, as pointed out by Edmunds (1975), the expected present-day dispersion in metallicity Z is $Z_1/\sqrt{n}$, where Z_1 is the present-day metallicity and n is the number of SNRs contributing to Z_1 at any given point. For the solar neighborhood, this predicts a present fractional dispersion in metallicity of roughly 10^{-3}, which is orders of magnitude more uniform than the observed dispersion that is of order 10^{-1}.

Individual regions of contamination are not uniformly identical, however. Thus, in constructing a quantitative model for Simple Inhomogeneous Evolution (SIM), we adopted a metallicity distribution function (MDF) $f(Z)$ for the unit patches that build up a system's metallicity (Oey 2000). Instead of individual SNRs, the products from core-collapse supernovae (SNe) are assumed to be distributed via superbubbles resulting from the spatial correlation of SNe in OB associations. Oey & Clarke (1997) showed that most ordinary superbubbles at some stage become pressure-confined, resulting in final radii R that are related to the input mechanical luminosity L as $R \propto L^{1/2}$; thus the total superbubble volume $V \propto L^{3/2}$. The total mass of new metals produced by these same SNe, however, is directly proportional to L. We therefore find that

$$Z \propto L^{-1/2} \propto R^{-1} \tag{1}$$

for any given superbubble, implying that the larger objects yield lower metallicity because of the dilution into greater volume. Based on the empirical H II region luminosity function and OB association mass function, Oey & Clarke (1997) derived a size distribution for superbubbles $N(R) \propto R^{-3}$. Together with equation 1, we therefore have

$$f(Z) \propto Z^{-2} \tag{2}$$

for the parent MDF of contaminating patches at any given point in the ISM (Oey 2000).

Of equal importance as the functional form for $f(Z)$ is its characteristic mean metallicity δZ. If δZ is small, then a system requires more generations of star formation at any given point to build up to a given present-day Z_1. Thus we see that the relationship between the SN yield and interstellar mixing is critical in determining both δZ and also the range of $f(Z)$. Assuming no mixing beyond the final superbubble radius, and taking fiducial maximum and minimum superbubble radii of 1300 and 25 pc, yields extreme metallicities corresponding to $[\mathrm{Fe/H}]_{\mathrm{min}} = -2.6$ and $[\mathrm{Fe/H}]_{\mathrm{max}} = -0.6$. Since metal-poor stars show metallicities ranging continuously down to $[\mathrm{Fe/H}] \sim -4.0$, this demonstrates that metals must mix in the ISM much farther beyond the superbubble radius. Note that throughout this contribution, [Fe/H], as the principal stellar metallicity indicator, is used as a surrogate for metallicity resulting from Type II SNe. We do not consider here the evolution of products from lower-mass stars.

3. Interstellar mixing processes

Thus we are led to consider the physical processes of mixing in the interstellar medium. The conventional view of the global ISM has been that of distinct hot (10^6 K), warm (10^4 K), and cold (10^2 K) phases in rough pressure equilibrium. However, recent studies are instead suggesting that, while these temperature phases do exist, as they must because of the cooling function, they appear to be less distinct than has been thought (e.g., Vázquez-Semadeni 2002; Kritsuk & Norman 2002). The cool clouds, in particular, are apparently transient, unconfined features. This new characterization of the ISM suggests even more strongly that turbulent processes are likely to dominate kinematics.

Turbulence has already been implicated in the past by the apparent existence of hierarchical scales for energy injection. Roy & Kunth (1995) argued that mixing timescales for small-scale processes are consistently less than those for large-scale processes. They considered large, intermediate, and small scales respectively driven by galactic rotation and shear, superbubbles and cloud collisions, and molecular diffusion. The observed spatial power spectrum of structure in the ISM is consistent with such hierarchical energy input, which plausibly drives an energy cascade resulting in a Kolmogorov power-law, compatible with the observed spatial power spectrum in the ISM (e.g., Lazarian 2002; Scalo 1987). Thus turbulence has been identified by a number of authors as the dominant agent for mixing in the ISM (e.g., Roy & Kunth 1995; Tenorio-Tagle 1996).

We therefore consider the two primary candidates for mass transport to be atomic diffusion and turbulent mixing. While previous studies have also considered cloud collisions (Bateman & Larson 1993; Roy & Kunth 1995), this process appears less viable for the new paradigm of transient, unconfined cold clouds. It also requires the cloud velocities to be larger than the random velocities of the ISM associated with the other transport mechanisms. Thus we defer consideration of cloud collisions to the mentioned references. Oey (2002) recalculates the diffusion coefficients for different ISM temperature phases. Table 1 confirms, from a more detailed analysis, the finding by Tenorio-Tagle (1996) that diffusion is a highly inefficient process for mass transport, even for the hot ionized medium (HIM).

Table 1. Parameters for O diffusion in diffuse ISM

Phase	T (K)	n(H) (cm^{-3})	O ion	log D_{12} ($\mathrm{cm}^2\ \mathrm{s}^{-1}$)	r_{rms} [a] (pc)
CNM	1×10^2	1.0	O^0	18.25	0.06
WNM	8×10^3	0.3	O^0	20.72	1.0
WIM	1×10^4	0.1	O^{+2}	18.04	0.05
HIM	1×10^6	0.003	O^{+5}	23.64	30

[a] Diffusion length for 1×10^8 yr.

While turbulent processes are difficult to quantify, we describe here some crude estimates (see Oey 2002 for details). Bateman & Larson (1993) give an expression for the characteristic mixing distance:

$$r_{\rm trb} = (2/3\ v_{\rm trb}\ l_{\rm trb}\ t)^{1/2} = 58.3\ (v_{\rm trb}/{\rm km\ s^{-1}}\ )^{1/2}\ {\rm pc} \quad , \tag{3}$$

where $v_{\rm trb}$ and $l_{\rm trb}$ are the turbulent velocity and associated length scale, respectively; and the coefficient 58.3 results for $l_{\rm trb} = 50$ pc and $t = 1 \times 10^8$ yr. Thus we see, in comparison with Table 1, that turbulence is orders of magnitude more efficient than diffusion.

In estimating the mixing time for newly synthesized elements originating in hot superbubble interiors, we argue that the most efficient length scale is that associated with the size of the considered region, namely, the superbubble radius: $l_{\rm trb} \sim R$. To uniformly mix in the ISM, and especially, to become incorporated in subsequent star formation, the metals need to cool. For turbulence, heat transport and mass transport are analogous processes, therefore turbulence most likely dominates the cooling process as well. We assume that we need roughly an order of magnitude more cool particles than hot particles to cool the hot gas by turbulent heat transport (and assistance from the cooling curve), thus yielding rough estimates:

$$t_{\rm cool,W} \simeq 0.15\ l_{\rm trb}({\rm pc})\ \ {\rm Myr} \quad ({\rm WM}) \tag{4}$$
$$t_{\rm cool,C} \simeq 0.97\ l_{\rm trb}({\rm pc})\ \ {\rm Myr} \quad ({\rm CNM})\ , \tag{5}$$

for $v_{\rm trb} = 16$ km s^{-1} and 1.6 km s^{-1} for cooling into warm medium (WM; both neutral and ionized) and cold neutral medium (CNM), respectively. These expressions are comparable to similar analytic estimates by de Avillez & Mac Low (2002). Assuming that new metals need at least this cooling time to join the WM or CNM, equations 4 and 5 suggest they can mix out to

$$r_{\rm mix} = 2^{-1/3}\epsilon_2\Big(\frac{v_1}{v_2}\Big)^{1/2}\ R \quad ({\rm WM,HIM}) \tag{6}$$

$$r_{\rm mix} = \Big[\frac{2}{3}v_2 R\ (\tau_n - t_{\rm cool,C} - t_f)\Big]^{1/2} \quad ({\rm CNM}) \tag{7}$$

where subscripts 1 and 2 denote parameters for the dispersing and ambient media, respectively, and ϵ is a factor depending on their density ratio. The star formation duty cycle timescale is represented by τ_n and t_f is the age at which the parent superbubble attains its final pressure-confined radius. For a density ratio $n_1/n_2 = 0.1$ and $v_1/v_2 = 10$, equation 6 reduces to $r_{\rm mix} = \sqrt{10}\ R$. Thus, we estimate a characteristic dispersal length that depends on the balance between the different ISM temperature phases:

$$r_{\rm mix,tot} = \Big[R^3 + f_{\rm C} r_{\rm C}^3 + f_{\rm W} r_{\rm W}^3 + f_{\rm H} r_{\rm H}^3\Big]^{1/3} \quad , \tag{8}$$

where $f_{\rm C}$, $f_{\rm W}$, and $f_{\rm H}$ are the mass fraction of cold, warm, and hot ISM, respectively. The ISM phases are assumed to be individually continuous, and, for cooling by turbulent mixing to dominate, requires $f_{\rm C} > f_{\rm W} > f_{\rm H}$.

Figure 1*a* shows limits for the characteristic dispersal length $r_{\rm mix,tot}$ as a function of parent superbubble radius R for $\tau_n = 500$ Myr (dashed lines) and 200 Myr (solid lines), as given by equations 6 – 8. We see that the the relation

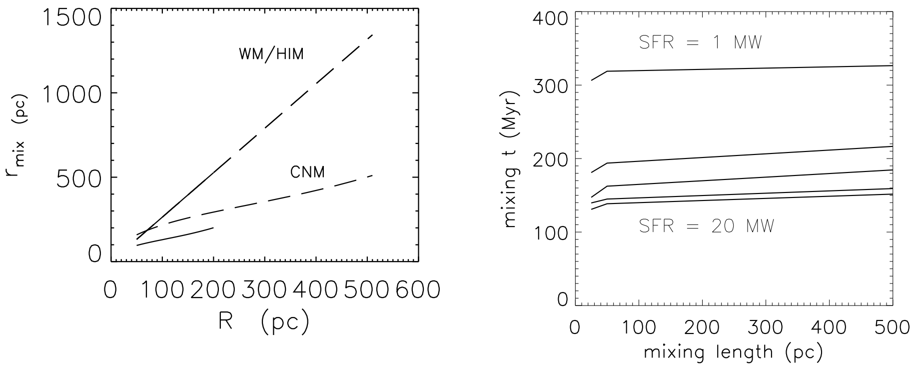

Figure 1. (a) Limits for dispersal length $r_{\rm mix,tot}$ estimated from equations 6 – 8, for $\tau_n = 500$ (dashed) and 200 Myr (solid), respectively. (b) Mixing time as a function of mixing length from Table 1 of de Avillez & Mac Low (2002), for SN rates of 1, 5, 10, 15, and 20 times the Galactic rate.

between R and $r_{\rm mix,tot}$ is virtually linear, with a slope between 0.7 and 3.1. This suggests we may crudely estimate that metals synthesized by massive stars are dispersed to radii up to ~ 3 times the original superbubble radius.

That the metals disperse to large distances while within the HIM has been suggested by, e.g., Kobulnicky (1999). Starburst galaxies show spatial uniformity in nebular abundances to $\lesssim 0.2$ dex with no evidence of self-enrichment near major star-forming complexes; NGC 1569 is a notable example where metal production expected from the supercluster A must be dispersed within a diameter of at least 100 pc to explain the observed abundance uniformity (Kobulnicky & Skillman 1997). One of the only existing candidate counter-examples are provocative observations by Cunha & Lambert (1994) that suggest a metal-enriched sub-group of stars within the Orion Nebula.

In addition, actual hydrodynamical simulations of turbulent mixing processes are finally beginning to be realized. De Avillez & Mac Low (2002) carry out such a study using a 3D, PPM, 3-level adaptive mesh refinement code. They assume a multi-temperature, density-stratified ISM with turbulence driven exclusively by SNe. Intriguingly, they find that the mixing time in their simulations is essentially independent of the mixing length. Figure 1b plots the mixing time as a function of mixing length from their Table 1, for different SN rates. This surprising result, which contradicts conventional mixing length theory, clearly bears further investigation. More intuitively, they find that the mixing time is more sensitive to the input SN rate (see Figure 1b). Note that for SN rates of 1 – 10 times the Galactic rate, the mixing timescales are of order a few times 10^8 yr, as we estmate above.

4. Consequences for chemical evolution

With a coarse idea for mixing timescales and corresponding dispersal lengths, we now revise the estimates for the MDF $f(Z)$ of the parent metallicities that drive galactic chemical evolution. Earlier above, we used the superbubble radii themselves as characteristic dispersal lengths. In that case, the fiducial maximum and minimum radii of 1300 and 25 pc correspond to the unrealistically high values of minimum and maximum [Fe/H] of –2.6 and –0.6, respectively. These estimates can now be reduced by roughly an order of magnitude, since we found above that new metals are dispersed into a volume roughly an order of magnitude greater during their cooling time. Thus we obtain a range for the parent $f(Z)$ corresponding to $-3.6 \lesssim$ [Fe/H] $\lesssim -1.9$. This implies a characteristic mean value for the typical enrichment unit δZ of [Fe/H] ~ -3.0. Argast et al. (2000) use a similar stochastic approach for their simulation of chemical evolution based on contamination by individual SNRs; we note that they adopt δZ of [Fe/H] ~ -2.8. Thus, there is some reassurance that these independent models assume similar values.

Note that the lowest observed metallicities may offer an important constraint on the minimum values of the parent MDF. For a closed-box model, Audouze & Silk (1995) emphasize the existence of a low-metallicity threshold $Z_{\rm min}$ for $f(Z)$: in a system with no global homogenization, there can be no regions with metallicities between zero and $Z_{\rm min}$ of the enrichment units. It has been suggested that the currently observed low-metallicity limit of [Fe/H] ~ -4.0 for Galactic halo stars (Beers 1999) represents such a real threshold. If so, then our crudely estimated $[{\rm Fe/H}]_{\rm min}$ is reasonably consistent with this value. Additional uncertainty in our estimate results from the assumed SN yield of 10 $M_\odot$ of metals per SN; this value could be reduced by up to an order of magnitude, further improving the rough estimate with observations. It is thus of great interest to determine whether the empirical threshold indeed exists.

The enrichment units represented by $f(Z)$ can now be used to drive models for inhomogeneous chemical evolution. As described above, we argued that $f(Z) \propto Z^{-2}$ within the $Z_{\rm min}$ and $Z_{\rm max}$ modified above. The Simple Inhomogeneous Evolution model of Oey (2000) can then be used to predict the expected dispersion in present-day metallicity resulting from pure inhomogeneous evolution. Note that in the presence of homogenization, the system would then tend toward description by the homogeneous Simple Model.

Figure 2 shows predicted instantaneous MDFs for two systems, assuming the parent $f(Z)$ estimate above: $f(Z) \propto Z^{-2}$, $-3.6 <$ [Fe/H] < -1.6. For the model evolved to $\sim 0.1 Z_\odot$, we find a predicted [O/H] dispersion of 0.28 dex, and for the model evolved to $\sim Z_\odot$, the predicted dispersion is 0.13 dex. (See Oey 2002 for the conversion between [O/H] to [Fe/H].) Observations of the metallicity dispersion in the solar neighborhood do appear to be in reasonable agreement: new abundances of 70 B stars by Daflon & Cunha (this volume) show a scatter of around 0.2 dex, and measurements from lower-mass field stars and open clusters by Twarog et al. (1997) show a dispersion of around 0.1 dex around the solar circle. The age-metallicity relation in the solar neighborhood shows a dispersion of order 0.2 dex for the youngest F and G stars (Edvardsson et al. 1993).

The interstellar deuterium abundance deserves special mention: since the evolution of D/H is driven almost exclusively by depletion from the cosmological abundance by star formation, predictions for present-day D/H are independent of any stellar yields. This different evolution process for D/H therefore will offer

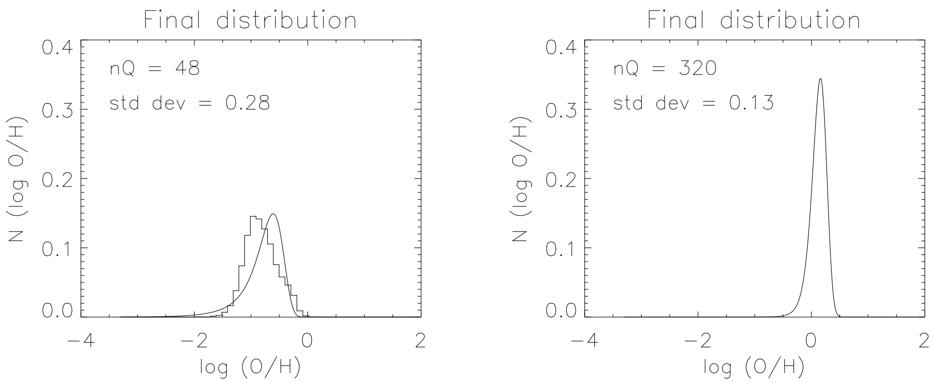

Figure 2. Instantaneous metallicity distribution functions predicted by a SIM model for systems at roughly 0.1 $Z_{\odot}$ and 1.0 $Z_{\odot}$. These correspond to predicted standard deviations in metallicity dispersion of 0.28 dex and 0.13 dex, respectively. The model assumes a characteristic enrichment event δZ of [O/H] ~ -2.4 (see text for details).

an important independent constraint on chemical evolution (see, e.g., Clayton 1985; Tosi et al. 1998; de Avillez & Mac Low 2002), although to date no quantitative model exists for interpreting the dispersion in D/H. Recent observations of the local D/H abundance from *FUSE* and *IMAPS* are revealing a dispersion of ~ 0.15 dex at distances of a few 100 pc from the sun (e.g., Moos et al. 2002; Sonneborn et al. 2000; Jenkins et al. 1999). Within the Local Bubble, D/H is significantly more uniform, as expected for efficient mixing within its hot gas.

Beyond the Milky Way, observations of nearby dwarf starburst galaxies like NGC 4214, NGC 1569, and NGC 5253 (Kobulnicky & Skillman 1996, 1997; Devost et al. 1997) have been found to show nebular abundance dispersions of $\lesssim 0.2$ dex. Similar dispersions are found from A and F supergiant abundances in Local Group dwarfs like NGC 6822 (see Venn, this volume). It has been suggested that the abundance dispersions are unexpectedly uniform, but as shown above, our Simple Inhomogeneous Models estimate metallicity dispersions of roughly 0.1 – 0.3 dex in the range 0.1 – 1 $Z_{\odot}$ that are represented by these galaxies. For the current empirical accuracy and large model uncertainties, the comparison between observations and predictions still looks good. There is, however, lack of evidence for self-enrichment, as noted in §2 above, which is consistent with the extended cooling times of order 10^8 Myr determined above. It is somewhat unclear whether the currently reported dispersions are close to real values or represent upper limits, and it is thus vital to determine them more accurately.

An important feature of inhomogeneous chemical evolution is the expectation of increasing scatter at low metallicities: the dispersion is naturally larger when stochastic enrichment dominates, as it does in the earliest stages when $Z \sim \delta Z$. (Audouze & Silk 1995). Such an increase in stellar abundance dispersions is well-known to exist, especially for abundance ratios, at [Fe/H] $\lesssim -1.5$ (e.g., McWilliam et al. 1995; Ryan et al. 1996). Stochastic simulations by Argast et al. (2000) indeed reproduce many features of this pattern in the dispersion, and as is evident above, our SIM models also show this trend. However, observational discrepancies exist, in particular the extremely metal-poor dwarf galaxy I Zw 18. While the above stellar dispersions are $\gtrsim 0.5$ dex, the nebular abundances of [O/H] show a typical scatter of $\lesssim 0.15$ dex (Vílchez & Iglesias-Páramo 1998; Legrand et al. 2000). Thus the present-day metallicity of I Zw 18 is significantly more uniform than expected from our purely inhomogeneous model. This suggests that the system homogenizes on a timescale faster than the star formation duty cycle. Such homogenization could be facilitated by different factors: a) The galaxy's small size (~ 1 kpc) shortens both the homogenization length and time scale; b) a high star formation rate would shorten the homogenization time scale (de Avillez & Mac Low 2002); and c) the small gravitational potential could allow the bulk of new metals to be ejected from the galaxy, lengthening the effective star formation duty cycle. Hence, understanding the transport of metals in this and similar galaxies offers vital leverage on the mixing and homogenization processes in general.

5. Conclusion

In summary, the dispersal of newly synthesized elements takes place on at least three scales: localized mixing, global homogenization, and outflow/inflow from the system. It has emerged that the transport mechanisms are dominated by turbulence. The dispersal length scale for localized mixing determines the dilution of new metals in the ISM, and therefore sets the MDF of the parent enrichment units $f(Z)$ that drive chemical evolution. We crudely estimate that, depending on the balance of ISM temperature phases, the hot, metal-bearing gas will have cooling times of order 10^8 yr and disperse to roughly a decade in distance beyond the original radius of the superbubble created by the SNe. This is consistent with analytic and numerical hydrodynamical simulations of mixing by de Avillez & Mac Low (2002). An important constraint on the minimum values for $f(Z)$ should be given by the observed low-metallicity threshold; we find that the current observed limit of [Fe/H]~ -4 for halo stars (Beers 1999) is compatible with our crude, order-of-magnitude estimate.

This rough understanding of element dispersal and corresponding estimate for the $f(Z)$ of individual enrichment units can then be incorporated into Simple Inhomogeneous Models for chemical evolution. These yield estimates for the present-day dispersion in metallicity, which may be compared with observations. We estimate dispersions of 0.1 – 0.3 dex in the metallicity range $0.1 - 1.0 Z_\odot$, which is thus far consistent with data for the solar neighborhood, Local Group galaxies, and several nearby starburst galaxies, thereby suggesting that global homogenization is thus far unnecessary to explain observations. However, the scatter in abundance is expected to increase at lower metallicities. While this is seen in Milky Way stellar abundances, the extremely metal-poor galaxy I Zw 18 shows metallicities that are more uniform than expected from the SIM. This implies that this galaxy has a faster homogenization time relative to its star formation duty cycle, perhaps caused by its small size, high star formation rate, and/or outflow of hot, metal-bearing gas. It is evident that our understanding of these processes are still rudimentary, and more data and modeling are necessary.

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