# A NEW LOOK AT INHOMOGENEOUS CHEMICAL EVOLUTION

**M. S. Oey**

*Space Telescope Science Institute*
*3700 San Martin Drive, Baltimore, MD, 21218, USA*
*e-mail:* oey@stsci.edu

I present a simple, one-zone, analytic model for inhomogeneous chemical evolution, in the limit of no mixing. This model incorporates an ISM filling factor $Q$ of newly-enriched gas, and $Q$ is as important as the number of generations of star formation. This model can match the metallicity distributions of long-lived stars in the Galactic halo without invoking gas infall or pre-enrichment, and offers an alternative to the Simple, closed-box Model for interpreting the metallicities. The G-dwarf Problem for the Galactic disk also slightly improves.

## INTRODUCTION

The study of galactic chemical evolution has developed such that we now have complex, chemodynamical codes (*e.g.*, Hensler & Burkert, 1990; Bradamante *et al.*, 1998; Berczik, 1999) to model observations of abundance patterns. They include a large number of free parameters, including inflow, outflow, radial flow, pre-enrichment, stellar initial mass function, variable star formation rate, *etc.* These codes are designed to address signatures of chemical evolution such as the time-integrated metallicity distributions of low-mass stars; element ratios; and age-metallicity relations. However, the *instantaneous* metallicity distribution function (MDF) at any given time, is a major diagnostic of chemical evolution that has yet to be fully exploited.

Most models consider only homogeneous evolution of a fully mixed system. Yet, Tinsley (1975) demonstrated that inhomogeneous evolution can have significant consequences for *all* of the resulting chemical signatures. In addition, Edmunds (1975) remarked that the dispersion in the MDF should decrease with time, as the individual enrichment units become a progressively smaller fraction of the mean metallicity level. This underappreciated point is relevant to the evolution of age-metallicity relations, but is rarely discussed. Edmunds showed that the most simplistic inhomogeneous evolution of overlapping supernova remnants, with no mixing, yields a present-day ISM that is orders of magnitude *more* homogeneous than what is presently observed. This issue has likewise received only occasional attention (*e.g.*, Roy & Kunth, 1995).

I, therefore, examine here the simplest consequences of purely inhomogeneous evolution, and compare the results to analogous analytic models, and observations. The standard approach for existing inhomogeneous chemical evolution models (*e.g.*, Malinie *et al.*, 1993; Pilyugin, 1993; Searle, 1977) is to adopt a given metallicity or age dispersion among an ensemble of regions that independently evolve according to the homogeneous Simple, closed-box Model (*e.g.*, Pagel & Patchett, 1975; Schmidt, 1963). Instead, the model summarized here from Oey (2000) predicts the form itself of the instantaneous MDF and its evolution.

## INHOMOGENEOUS CHEMICAL EVOLUTION FROM FIRST PRINCIPLES

The basis is simple: random overlapping regions of contamination drive the chemical evolution, including the instantaneous MDF. There is no mixing at any time between the individual contaminating regions. We consider $n$ generations of these individual star forming regions, *and each generation occupies a filling factor* $Q$ in the ISM. This implies that the final, instantaneous MDF after $n$ generations is,

$$N_{\rm ins}(z) = \sum_{j=1}^{n} P_j \; N_j(z), \tag{1}$$

where $P_j$ is the probability of occurrence for $j$ overlapping objects, and $N_j(z)$ is the MDF for regions having $j$ overlapping objects. For the situation described, $P_j$ is given simply by the binomial distribution in parameters $Q$ and $n$:

$$P_j = \binom{n}{j} \; Q^j \; (1-Q)^{n-j}, \quad 1 \le j \le n. \tag{2}$$

The component distributions $N_j(z)$ approach normal distributions for large $j$, according to the Central Limit Theorem, provided that the metallicity distribution of parent enrichment events $f(z)$ remains constant. However, for small $j$, $N_j(z)$ depends on $j$ and the form of $f(z)$. Oey (2000) argued that $f(z)$ should be a decreasing power-law:

$$f(z)\,dz \propto z^{-2}\,dz, \quad z_{\rm min} < z < z_{\rm max}. \tag{3}$$

This is based on observations that the H II region luminosity function (H II LF) is a power-law, and the associated size distribution of superbubbles generated by the parent Type II SNe is also a power-law (Oey & Clarke, 1997, 1998). The exponent of –2 (equation 3) assumes uniform distribution of the metal production into the volume of the superbubbles, and depends on the parent slope of the H II LF. Likewise, $z_{\rm min}$ and $z_{\rm max}$ are determined by the maximum and minimum sizes of the superbubbles, along with the SN yield. One can then compute Monte Carlo models for the components $N_j(z)$, for small $j$, by drawing $j$ times from equation 3 and combining these. Equation 1 then yields the instantaneous MDF, using either Monte Carlo (small $n$) or analytic (large $n$) methods.

Likewise, the total, time-integrated MDF can be computed over all generations by,

$$N_{\rm tot}(z) = \frac{1}{n}\sum_{k=1}^{n} D_{k-1}\ N_{{\rm fin},k}(z), \tag{4}$$

where $D_k$ is the fraction of original gas remaining after $k$ generations, and $N_{{\rm fin},k}(z)$ is $N_{\rm fin}(z)$ for each generation $k$. This may then be compared to observations of long-lived stellar populations.

## COMPARISON TO THE GALACTIC DISK AND HALO

This model predicts that the evolutionary state of a system is described by the mean of the binomial distribution, $nQ$ (Oey, 2000). This is an important contrast from most other models, which are driven only by $n$, the number of generations. Since $n$ is associated with age, and $Q$ with global star formation efficiency, the combined parameter $nQ$ offers a simple way to understand various combinations of age and metallicity. For example, a given $nQ$ having a relatively high value of $Q$ can explain a system with simultaneously ancient, yet high-metallicity stars (*e.g.*, the Galactic bulge); while a relatively low value of $Q$ can explain a system that is presently metal-poor, yet shows the presence of old stars (*e.g.*, I Zw 18).

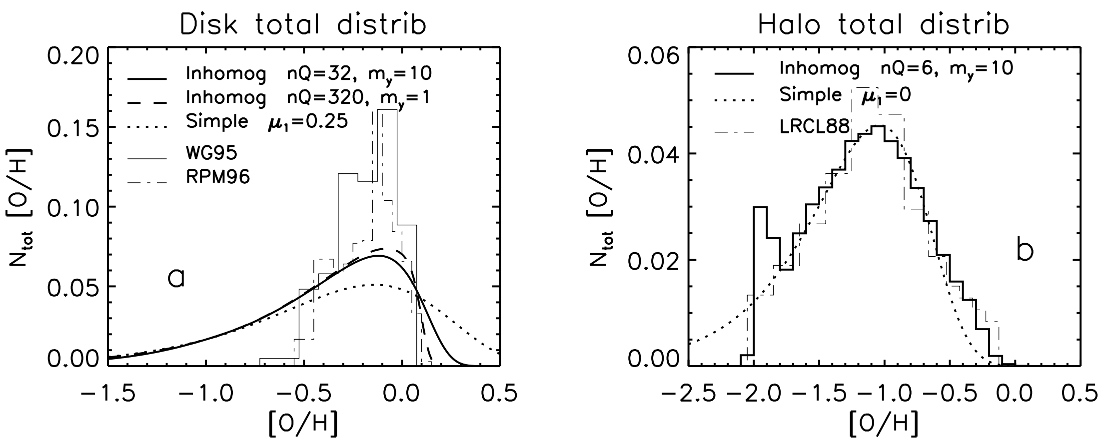


Figure 1: The empirical disk MDFs ($a$) from Wyse & Gilmore (1995) and Rocha-Pinto & Maciel (1996) is overplotted by an inhomogenous model with mean SN yield $m_y = 10\,{\rm M}_\odot$ (solid line); and a more evolved model having a yield of $1\,{\rm M}_\odot$ (dashed line). The dotted line shows the Simple Model for present-day solar metallicity. All disk models adopt $\mu_1 = 0.25$. The empirical halo MDF ($b$) from Laird *et al.* (1988) is overplotted by a Monte Carlo inhomogeneous model for $nQ = 6$ and $m_y = 10\,{\rm M}_\odot$ (solid line), and a Simple Model with present-day mean [O/H]$= -0.2$. Both halo models have $\mu_1 = 0$

Figure 1*a* shows the Galactic disk F/G-dwarf MDF in the solar neighborhood, as derived by Wyse & Gilmore (1995) and Rocha-Pinto and Maciel (1996). The dotted line shows the homogeneous Simple Model, where the consumption of gas to form stars leaves a present-day gas fraction $\mu_1 = 0.25$. The deviation of this model from the data clearly demonstrates the "G-dwarf Problem". The heavy, solid line shows the analytic, inhomogeneous model, for $nQ = 32$ and mean SN yield $m_y = 10\,\mathrm{M}_\odot$. The dashed line shows a model with a lower yield, $m_y = 1\,\mathrm{M}_\odot$, which is thereby 10 times more evolved for the given mean metallicity. Both these models also take $\mu_1 = 0.25$. The inhomogeneous models show a skewed distribution, and, although the G-dwarf Problem is still present, they are more similar to the data than the Simple Model. This has consequences for the form and rate of implied gas infall that is often used to explain the observed Galactic disk MDF. Malinie *et al.* (1993) emphasized the importance of also matching the high-metallicity tail of the MDF, and it is noteworthy that the inhomogeneous models are clearly better able to match the sharp drop-off in the data.

In fact, for this model, the high-metallicity tail of the MDFs can be an important probe of the parent $f(z)$ for each generation. Figure 1*b* shows the MDF for F/G-dwarfs in the Galactic halo from Laird *et al.* (1988; dot-dashed line). The Monte Carlo model for $nQ = 6$ is overplotted with the solid line. There is excellent agreement between the inhomogeneous model and the data. These halo data also agree with the Simple Model, shown by the dotted line, for $\mu_1 = 0$ and mean present-day metallicity [O/H] $= -0.2$. However, it is essential to note that *the shapes of the two models result from entirely different processes.* The high-metallicity turnover in the Simple Model results only from the consumption of gas into stars. In contrast, the high-metallicity tail of the inhomogeneous model represents the vestige of the $f(z)$ power-law; while the low-metallicity turnover results from the Central Limit Theorem, as the component distributions progress toward gaussians. (Note that in the limit of large $nQ$, the MDF will qualitatively have the form of the inhomogeneous models shown in Figure 1*a*.) Thus, the halo model (a) offers an alternative understanding/interpretation of the MDF *vs.* the Simple Model, and (b) reveals the importance of the high-metallicity tail in relatively unevolved systems, for probing the parent distribution $f(z)$.

**Acknowledgements.** I am grateful to Cathie Clarke, Mike Fall, and Rosie Wyse for discussions and suggestions.

## REFERENCES

[1] *Berczik P.* // Astron. and Astrophys.–1999.–**348**.–P. 371.

[2] *Bradamante F., Matteucci F., D'Ercole A.* // Astron. and Astrophys.–1998.–**337**.–P. 338.

[3] *Edmunds M. G.* // Astrophys. and Space Sci.–1975.–**32**.–P. 483.

[4] *Hensler G., Burkert* // Astrophys. and Space Sci.–1990.–**170**.–P. 231.

[5] *Laird J. B., Rupen M. P., Carney B. W., Latham D.* // Astron. J.–1988.–**96**.–P. 1908.

[6] *Malinie G., Hartmann D. H., Clayton D. D., Mathews G. J.* // Astrophys. J.–1993.–**413**.–P. 633.

[7] *Oey M. S.* // Astrophys. J. Lett.–2000.–in press, astro-ph/0008302.

[8] *Oey M. S., Clarke C. J.* // Mon. Notic. Roy. Astron. Soc.–1997.–**289**.–P. 570.

[9] *Oey M. S., Clarke C. J.* // Astron. J.–1998.–**115**.–P. 1543.

[10] *Pagel B. E. J., Patchett B. E.* // Mon. Notic. Roy. Astron. Soc.–1975.–**279**.–P. 882.

[11] *Pilyugin L. S.* // Astron. and Astrophys.–1993.–**277**.–P. 42.

[12] *Rocha-Pinto H. J., Maciel W. J.* // Mon. Notic. Roy. Astron. Soc.–1996.–**279**.–P. 882.

[13] *Roy J.-R., Kunth D.* // Astron. and Astrophys.–1995.–**294**.–P. 432.

[14] *Schmidt M.* // Astrophys. J.–1963.–**137**.–P. 758.

[15] *Searle L.* // The Evolution of Galaxies and Stellar Populations / Eds B. M. Tinsley, R. B. Larson.–New Haven: Yale U. Obs., 1977.–P. 219.

[16] *Tinsley B. M.* // Astrophys. J.–1975.–**197**.–P. 159.

[17] *Wyse R. F. G., Gilmore G.* // Astron. J.–1995.–**110**.–P. 2771.