THE CHEMICAL EVOLUTION OF THE GALAXY

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1. INTRODUCTION

Over the last few years, our picture of the chemical evolution of the Galaxy has changed substantially. These changes are of interest because chemical evolution provides a common point of contact for most astrophysical processes of importance to galaxy evolution. By astrophysical processes we mean star formation, stellar nucleosynthesis, gas dynamics, etc. An understanding of galactic chemical evolution would allow us to place constraints on all of these topics simultaneously. This property, however, is a double-edge sword because, with so many variables involved, unique solutions to problems in chemical evolution are almost impossible.

The review is restricted to those areas, both observational and theoretical, where a consensus of opinion appears to be emerging on some of the major components of chemical evolution, particularly those which deviate from the simple, closed models. By necessity, many important topics will be ignored while others will reflect the particular bias of the reviewer. Detailed discussions can be found in a number of excellent reviews which have appeared in the last few years by Tinsley (1980a), Pagel and Edmunds (1981), and Mould (1982).

As a reference point, [Fe/H] refers to the logarithmic iron abundance relative to the Sun on a scale where 47 Tuc and M71 have [Fe/H] = -0.8, and -0.6, respectively.

2. THE SIMPLE, CLOSED MODEL

The classical starting point for discussions of chemical evolution is the simple, closed model. In this picture, the Galaxy is regarded initially as a closed box filled with gas of primordial composition, i.e., pure H and He. As the Galaxy ages, the gas is turned into stars, forming with a constant mass function. As a generation of stars evolves and dies, processed material is returned to the interstellar medium, while a significant fraction of the mass remains locked up in low-mass

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stars and stellar remnants. A critical parameter is the yield, y, the mass fraction of enriched material returned to the interstellar medium (ISM) relative to the mass locked up in low-mass and dead stars. The total yield for an element depends upon the mass function and the elemental yields as a function of stellar mass. The beauty of the model lies in the fact that the chemical history can be described by one equation

$$Z = y \ln \mu^{-1} \tag{1}$$

where Z is the metallicity of the gas, y is the yield, and μ is the gas fraction, the ratio of gas mass to total mass. If the initial mass function (IMF) is constant, the metallicity is dependent solely upon the gas fraction, independent of the star formation rate (SFR). It is assumed that the yield is recycled instantaneously and is well mixed. For twenty years, the classical G-dwarf problem (Schmidt 1963), a paucity of low-metallicity stars in the solar neighborhood, has been a dominant constraint on our picture of galactic evolution, with a variety of ad hoc assumptions presented to explain the failure of the simple model. Those features which now appear justified by observational evidence and their role in galaxy evolution will be discussed next.

3. COMPLEX, OPEN MODELS

The deviations from simplicity arise from the failure of a combination of assumptions. The specific areas of modification are:

3.1 The Continuity Question

The evolution of the Galaxy can be divided into two distinct phases, the halo and the disk; the conditions for star formation, the mass function, the degree of homogeneity, and the gas flows during these two phases are totally distinct. The metallicity distribution of the halo is very nicely matched by a simple, closed model as shown in Fig. 5 of Bond (1981), where the gas is initially enriched to [Fe/H] $\simeq$ -2.6, and the yield is constant at y = 0.018 $Fe_{\odot}$, where $Fe_{\odot}$ refers to the mass fraction of iron in the Sun. The characteristics of the solar neighborhood cannot be matched by a simple model and the halo yield for iron is forty times lower than that for the disk. Though the lower halo yield is consistent with the fragmentary-protocloud model of Searle (1977), the difference could result from a mass function weighted toward low-mass objects ($m < 0.1\ M_{\odot}$), a mass function deficient in Fe-producing stars of intermediate mass ($1\text{-}10 M_{\odot}$), and/or elemental stellar yields which are composition dependent. The only deficiency of the fragmentary protocloud model is that the disk must form out of the relatively unenriched gas lost by the clouds. Though theoretical models with infall of zero-metals gas indicate that the metallicity of such gas will rise rapidly to levels consistent with old-disk abundances, there should still exist an intermediate population of old disk stars with metallicities overlapping those of the halo. Though decisive information is lacking, the thick-disk component of the Galaxy found by Gilmore and Reid (1983) could

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represent this transition population. The boundary line between these two phases is tentatively adopted as [Fe/H] = -0.90 ± 0.2.

3.2 SFR History and the Age-Metallicity Relation

Despite the prompt initial enrichment phase provided by the halo (Ostriker and Thuan 1975), the simple model for the disk still fails. The age-metallicity data of Mayor (1976) and Twarog (1980) both indicate an approximately linear increase in the mean metallicity of the gas in the disk, Z_g, over most of its lifetime with a possible leveling off over the last 5×10^9 years. (See Fig. 2 of Pagel 1981) When combined with the metallicity distribution for the disk (Pagel and Patchett 1975), one can exclude models in which the present SFR is a small fraction of the average past SFR, i.e. less than 15%. From a variety of techniques, the best estimates for this parameter are constrained such that $0.5 \leq \langle SFR \rangle / SFR_o \leq 3$ (Mayor and Martinet 1977; Miller and Scalo 1979; Twarog 1980), where subscript zero refers to current values. Attempts at further restricting the SFR history through the use of the G-dwarf distribution seem unjustified. The detailed structure of the distribution is dominated by photometric and statistical uncertainties caused by the small sample (133 stars), the use of UBV photometry (McClure and Tinsley 1976), and velocity corrections.

The reasons for believing that the SFR in the past was significantly greater than the present are tied to two assumptions of the models which appear to be highly questionable: (1) no gas flows in or out of the system and (2) the SFR is proportional to the gas density to some power greater than or equal to one. The first of these will be discussed next while the second will be returned to later.

3.3 Infall

The value of using infall to explain some of the deviations from the predictions of the simple model has been recognized for some time (Larson 1972; Lynden-Bell 1975). The surprising result of the more recent discussions (Twarog 1980; Chiosi and Matteucci 1982; Vader and deJong 1981; Lacey and Fall 1983) is that, despite a wide range of model parameters, the need for a constant, moderate rise in metallicity combined with the current stellar and gas density inevitably requires an inflow of gas at a rate which is a significant fraction of the SFR, approximately 1/3 to 1/2. It must be emphasized that the crucial parameter dominating the chemical history is the ratio of infall to star formation. The need for infall on a galaxy-wide scale is consistent with the observation that most spirals have surprisingly short gas depletion timescales based on gas content and SFR estimates. (Larson, Tinsley, and Caldwell 1980; Kennicutt 1983) The nagging uncertainty in this picture of harmony is that not only do we not know the source of the infalling gas, but no conclusive evidence exists that there is extensive infalling gas. (See van Woerden et al., this volume, for more information.)

3.4 The Initial Mass Function (IMF)

Of all the assumptions used in chemical-evolution models, that of a constant IMF and/or yield is most often greeted with skepticism. The elemental production can vary with time because of a change in the slope of the mass function and/or the elemental yields as a function of stellar mass can vary as the composition changes. Unfortunately, our understanding of star formation and stellar nucleosynthesis is so poor that plausible arguments can be made supporting almost any direction of variability.

If one accepts the general premise that the mean metal abundance of the disk increases with time (irrespective of the rate), the best test of a variable IMF is a plot of an elemental abundance ratio with [Fe/H], where the dominant source of one element is the high-mass stars, e.g. O, while the second element comes from low-mass stars, e.g. Fe. If the yield ratio is constant, the abundance ratio is constant, independent of the SFR history. Fig. 2 of Twarog and Wheeler (1982) shows [O/Fe] vs. [Fe/H] for the disk based on elemental abundances of dwarfs. The halo shows an overabundance of O relative to Fe equivalent to [O/Fe] $\simeq$ +0.5. The transition between halo and disk is apparent at [Fe/H] $\simeq$ -0.9 ± 0.2. At first glance, it would appear that not only is the O/Fe production rate lower in the disk but variable as well. This is not the case. The disk data can be well represented by a model in which the yield ratio is constant but lower than in the halo. The variation in [O/Fe] is due to the initially high O abundance in the gas of the disk which gradually weakens due to disk production.

4. BEYOND THE SOLAR NEIGHBORHOOD

Our picture of disk evolution above is based solely on information obtained from stars within a few hundred parsecs of the Sun. As one moves outside this small sphere, the quantity and quality of the information relevant to chemical evolution declines dramatically and little of significance can be said about the temporal evolution of the system. However the data on the spatial distribution of the evolutionary parameters within a galaxy can be used to place crude constraints on the possible sources of different chemical histories among galaxies, and thereby may shed some light on the crucial factors controlling galaxy evolution.

4.1 Abundance Gradients

The spatial abundance distribution within the disk has been studied using a variety of objects, Cepheids (Harris (1981), G and K giants (Janes 1979), and supergiants (Luck 1982). A comprehensive discussion of the abundance gradient based on HII-region abundances can be found in the recent study of Shaver et al. (1983). The gradients observed for specific elements are listed in Pottasch, this volume. For those elements exhibiting significant gradients, the trend of increasing abundance with decreasing galactocentric distance is typical of that found in unbarred spirals (see e.g. McCall 1982). Extrapolation to the nuclear bulge indicates a metallicity approximately a factor of three above solar, consistent with recent claims based on studies of long-period variables (Wood and Bessell 1983) that the bulge contains a young population of super-metal-rich stars.

In a simple model, higher metallicity implies a greater degree of processing, i.e. a higher SFR per unit gas density. However, once the constraints of the closed model are removed, variation of any number of parameters can lead to higher current metallicities. In light of our picture of the solar neighborhood, it is felt that the dominant factor in the formation of an abundance gradient is the radial variation of the timescale for star formation relative to that for infall as exemplified by the dynamical collapse models of Tinsley and Larson (1978).

Crucial tests of this solution are the size of the gradient within the old disk, and the range in mean metallicity among spiral galaxies, particularly the early types. While it is possible to make the instantaneous metallicity of the disk gas abnormally high relative to the yield in an infall model with a high SFR relative to infall, the mean metallicity of the stars over the lifetime of the system can never be significantly higher than the yield, unless the infalling gas is metal-rich. The existence of an old, metal-rich population within the bulge may require: (1) radial gas flow of low angular momentum infall (Mayor and Vigroux 1981); (2) radial variations in the IMF (Garmony, Conti, and Chiosi 1982); or (3) a radial abundance gradient within a thick-disk population of the inner halo (Zinn 1980).

While the assumption of a higher infall rate nearer the galactic center rests on theoretical arguments regarding free-fall collapse timescales, a gradient in the SFR is supported by direct observation of high mass star-formation tracers, supernova remnants (Guibert, Lequeux and Viallefond 1978), and Lyc photons (Mezger 1978). The higher SFR is often produced in chemical-evolution models through the assumption that the SFR is some power-law function of the gas density or gas mass, a parameterization first used by Schmidt (1959). Numerous attempts to discover n, the power of the relation, have been inconclusive, implying that star formation is a multistep process dependent upon a number of factors in addition to the gas density. At least one factor appears to be the ability to make molecular clouds (see Young, this volume), which occurs at a higher rate near the galactic nucleus in most star-formation models. The observed decoupling of CO and HI distributions in our Galaxy and others would explain why a definite correlation between the SFR and HI has failed to emerge (Kennicutt 1983) and why some gas-rich galaxies show so little recent star formation (Schommer and Bothun 1983).

Beyond some critical distance where the SFR is low and the infall is a significant contributor over a long timescale, both models for star formation would predict that molecular-cloud formation declines sharply, possibly reverting to an evolutionary burst history similar to that in the halo. Such a transition between the two phases could explain the apparent steepening of the Fe-abundance gradient toward the galactic anticenter found by Janes (1979), while the O gradient maintains a constant slope. An ideal test of this picture and any chemical evolution model is provided by the irregular galaxies.

4.2 Irregulars and Chemical Evolution

For some time now, irregular galaxies have been extolled as unique objects for study because of their ability to fit the predictions of the simple closed model, i.e. Z is linearly correlated with ln μ^{-1}. This claim appears to be unjustified for two reasons: (a) Given the large uncertainties in μ and Z, the data for irregulars are not uniquely fit by a simple closed model. Over a wide range in μ, infall models can very closely mimic simple closed models in the Z - μ plane. In Figure 1a is plotted the O abundance vs. ln μ^{-1} for the solar-neighborhood infall model of Twarog and Wheeler (1982). The straight line is the prediction for a simple closed model within the disk with the same O yield as the infall model; (b) μ is normally calculated using dynamical estimates of the total mass (e.g. Lequeux et al. 1979). The assumption that all the mass is involved in chemical evolution is definitely unjustified in the solar neighborhood (Tinsley 1980b), where at least 1/3 to 1/2 of the disk material is in the form of dark matter. Whether or not a comparable problem exists in irregulars is unknown. The effect of adding such unseen matter to the total mass estimate is seen in Figure 1b, where 25% of the mass is in the form of dark matter uninvolved in chemical evolution. The effect is to steepen the slope of the relation, giving too large a yield.

Two recent studies of importance are those of Hunter, Gallagher, and Rautenkranz (1982) and McCall (1983). Both studies of HII regions in irregular and late-type spirals attempted fits to simple closed models, using gas fractions estimated with total masses based on assumed M/L ratios rather than dynamical estimates. Contrary to earlier studies, Hunter et al. found the irregulars as a group failed to match the predictions of the simple closed model using localized or galaxy-wide gas fractions. McCall found that HII regions in galaxies of type Scd or later fit the simple, closed model with an O yield of 0.0004, while earlier types deviated significantly from the prediction. If correct, this may imply that irregulars are not simple, isolated systems, but one extreme in a continuum of galaxy evolution influenced by gas flows.

5. SUMMARY AND SPECULATION

The topics of this talk have been those areas where supposedly our picture of chemical evolution of the Galaxy has changed for the better in recent years. However, two points cannot be overemphasized: (a) those areas of astrophysical importance to galaxy evolution where it can be said that our understanding is satisfactory, are meager, if not nonexistent, and (b) the degree to which we can claim to understand the chemical evolution of other galaxies is always significantly less than the degree to which we understand the chemical evolution of our own Galaxy. In light of (b), let me close by summarizing what our picture of

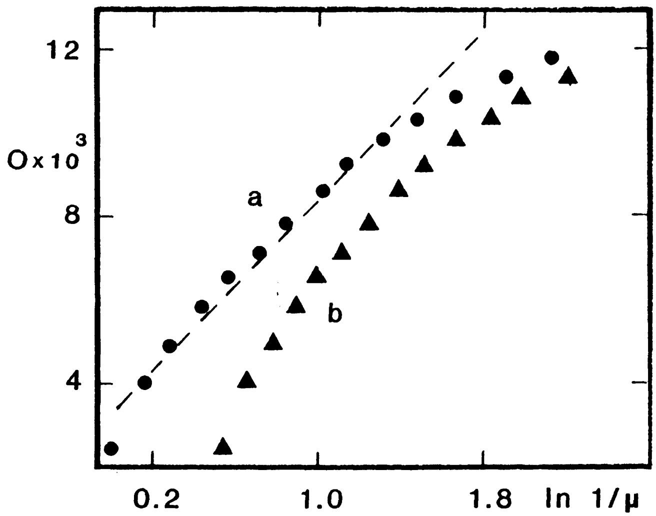

Fig. 1. Oxygen history for the solar neighborhood with (a) infall and (b) dark matter included.

the Galactic evolution may be telling us about chemical evolution of galaxies in general. Though the following statements are totally speculative, they are not original but represent a hybrid of ideas which have been stated or implied by a number of authors in the literature.

(1) Chemical evolution in spiral and irregular galaxies can be broken down into two distinct components: (a) a burst component similar to Searle's fragmented-protocloud model, characterized by large abundance inhomogeneities, reduced absolute yield but high O/Fe relative to the solar neighborhood, and little coherent spatial structure, and exemplified by the halo, the outermost regions of spirals, and irregular galaxies; (b) a continuous component, characterized by continuous star formation, a homogeneous ISM, yields typical of those in the solar neighborhood, and well-defined spiral structure as exemplified by early-type spirals, the solar neighborhood, and the inner regions of late-type spirals.

(2) All spirals and irregulars experience gas infall. The morphological trends along the Hubble sequence and radially within spirals have the same origin, the variation in the timescale for star formation relative to that for infall, with early-type galaxies and spiral nuclei having the highest rate of star formation relative to infall.

(3) The transition between the two phases among galaxies and within a galaxy is sharp and represents the point where molecular-cloud formation no longer occurs efficiently. Where this transition occurs is controlled by the mass distribution and the gas density which, in turn, is dominated by the variation of the star-formation to infall timescales within galaxies.

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DISCUSSION

J.P. Ostriker: Two questions: 1) Could the infall of metal-poor material not be supplied by evolving halo giants? 2) And conversely, could mass loss of metal-rich material (e.g. from type-I supernovae and runaway-star supernovae) leaving the Galaxy in a galactic wind remove the need for infall altogether?

Twarog: 1) Clearly you cannot have the gas come from too far out, for the reason you mentioned the other day: it would be inconsistent with the X-ray observations (see Discussion after paper by H. van Woerden in Section II.8). So, infalling material would have to come from the halo, within a constrained distance. Whether one can obtain it from halo stars, depends on the mass-loss rate of stars and on the star density in the halo.

Ostriker: In the model I made with Thuan several years ago, the early metal enrichment of the disk was from halo stars, and the late infall was hydrogen gas from halo stars - and both seemed to work out.

Twarog: 2) As to your second question, one could mimic a change in metallicity with time with such a model, but the star formation history also points to the need for infall and would be harder to reproduce in such an approach.

J. Milogradov-Turin: What do you mean when you say "halo" in the solar neighbourhood? Is it halo stars or the interstellar medium?

Twarog: What I call "halo", is stars with metallicity less than -1. This gets back to the matter of the thick disk (Section 3 of my paper). In Searle's picture of fragmenting proto-clouds, the gas falling into the disk has a range in metallicity from -2 to -1. So there should be disk-kinematic stars which have abundances like the halo. Hence the boundary between halo and disk is quite fuzzy.

R. Güsten: I disagree with two of your conclusions, namely the constant star-formation rate and the need for a high present-day infall rate.
1) The conclusion on the constancy of the star-formation rate (SFR) may be an overinterpretation of the stellar age-metallicity relation. Fits to the latter may also be obtained for the more reasonable assumptions of an exponentially decreasing infall rate and a e.g. linear dependence of the SFR on the available gas mass (see, for example, Vader and de Jong, 1981; Lacey and Fall, this meeting; Güsten and Mezger, 1983).
2) If you relax the instantaneous-recycling approximation, there is a natural flattening in the abundance gradients during late evolutionary phases, when evolved low-mass stars start diluting the ISM with 'metal'-poor ejecta.

Twarog: 1) The models do allow production of the age-metallicity relation using a star-formation rate which depends on the gas density via

some power law. However, this is irrelevant because all the observational tests to determine the exponent in this power law have been inconclusive: numbers between 0 and 3 have been found. And this is only to be expected, since star formation is far too complex a process to be described only by a simple function of the gas density. It has to be a combined function of gas density, molecular-cloud formation, composition changes, gas temperature, etc. Hence, even though parametrization may work in the models, I do not think it is relevant in terms of being physically correct. The constancy of the star formation rate is derived independently of the age-metallicity relation.
2) As to your second comment, I refer to the text of my paper.

V. Radhakrishnan: According to some supernova theories, a certain fraction of stars blow up completely, without leaving a neutron star behind. What can be said about the likelihood of such theories from the observed abundances?

Twarog: I had a point about that in my paper. Stellar-nucleosynthesis predictions for the abundances of O, Fe, Mg, Ne, etc. cannot be matched with continuous mass functions in which all stars above a certain mass contribute to chemical evolution. The only things you can do are to cut off the mass function, or to have it discontinuous. This may mean that we do not know enough about stellar nucleosynthesis to match the observations. There is no consistent theoretical prediction for stellar nucleosynthesis yields which will match the observations.

D. Lynden-Bell: Do the outermost HII regions in the galactic disk have the same O/Fe ratio as the halo or not?

Twarog: Unfortunately, there are hardly any data on this. One piece of information that we now have is C-abundance data from IUE on the Magellanic Clouds. C and Fe are made in the same stars, so their ratio is always 1. Dufour and Shields find that oxygen in the Magellanic Clouds is overabundant, relative to carbon, by about the same amount as in the halo: 0.3-0.7 dex.

Lynden-Bell: Does that indicate, then, that it is not really a matter of disk versus halo, but rather that the metal abundance is determined by the star-formation process?

Twarog: There are two modes of star formation, each with its own initial mass function. I used the terms "halo" and "disk", because these are the obvious examples of the two modes.

G.D. van Albada: How does your finding of a constant IMF tally with Kahn's and Viallefond's findings that at least the heavy end of the IMF strongly depends on the metallicity?

Twarog: Clearly it does not, but the observational tests for variation of IMF with metal abundance seem to be inconclusive so far.