PART V

FINAL REMARKS

FINAL REMARKS: CONNECTIONS BETWEEN CHEMICAL AND DYNAMICAL EVOLUTION

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Dynamical processes strongly affect the chemical enrichment of gas in galaxies, so abundances in stars and the interstellar medium can be used as probes of the dynamical history of the Galaxy. By way of tying together some diverse points, rather than summarizing the conference, I shall discuss some examples of connections between chemical and dynamical evolution. The first section of this paper mentions some of the well-known ways in which dynamical processes can affect chemical evolution, in order to outline a theoretical background to the use of abundances as clues to dynamics.

1. EFFECTS OF DYNAMICS ON CHEMICAL EVOLUTION

1.1. The star formation rate (SFR)

The SFR of course helps to govern the rate of chemical enrichment in a region of the Galaxy. Its fundamental importance was stressed in several papers here (e.g. Talbot's). In many respects, the rate itself is less important than ratios such as (SFR/gas flow rate) and (gas/mass/SFR) that determine the distribution of stellar compositions and the time scale for enrichment. If the SFR depends on stellar mass, i.e. if the initial mass function (IMF) is variable, there can be important systematic effects on stellar abundance distributions.

Many models in the literature have illustrated how chemical evolution can be affected by the SFR, IMF changes, and various rate ratios, time scales, etc. (see, for example, the review by Audouze and Tinsley [1976], to be referred to as AT). The point of interest here is that the possibilities suggested by various schematic models can be used, with data on chemical abundances, to probe the past SFR and related quantities in the Galaxy. Some examples will be discussed in § 2.

1.2 Interstellar gas dynamics

On small scales, the chemical homogeneity of the interstellar medium (ISM) depends on the time scale for mixing of stellar ejecta into the ambient gas; and clearly, the scatter in abundances of stars formed at similar times and places depends on the relation between this time scale and the lifetime of the ISM against star formation. Small-scale inhomogeneities have many interesting effects on the interpretation of abundances; for example, correlations among abundances of different elements are not immediately interpretable in terms of evolutionary trends (AT), and there can be systematic effects on nucleochronology if stars form preferentially in recently enriched regions (Reeves, 1972; Talbot and Arnett, 1973).

On larger scales, chemical evolution can be radically affected by gas flows, if these occur at rates comparable to the SFR (Larson 1972; AT; and other references cited below). Some examples related to infall and radial flows will be discussed in §2.

1.3 Galaxy formation

Relations between SFRs and gas flows during the formation of the Galaxy must have strongly affected the abundance distributions of stars and gas (as reviewed at this conference by Larson). A particularly interesting task for studies of chemical evolution is therefore to help unravel the process of formation of the Galaxy. Some questions that can be addressed in this way include the time scales for formation of the disk and spheroidal components of the Galaxy, and the efficiency with which supernova ejecta were mixed into the halo during its formation (see §2.1).

2. CHEMICAL CLUES TO DYNAMICAL EVOLUTION

On the basis of theoretical examples of how SFRs, gas flows, etc. can influence chemical evolution, abundance distributions can be used to suggest how such dynamical processes may have operated in the Galaxy. The following three cases refer to the halo, the whole disk, and the solar neighborhood, respectively.

2.1 The collapse rate and homogeneity of the halo

Stellar compositions have been used as probes of the dynamics of the collapse of the Galaxy ever since the classic work of Eggen, Lynden-Bell, and Sandage (1962). Recently, important new data and ideas have been published in this field.

Cowley, Hartwick, and Sargent (1977) have derived metal abundance indices for many globular clusters and three dwarf spheroidal galaxies extending to about 100 kpc from the galactic center. As reported by

Sargent (1977) and discussed further by Searle (1977), there is a wide spread of metallicities at each radius, extending to greater values inside 20 kpc than further out, but beyond 20 kpc there is no further systematic negative gradient. The interest in these results is that gradients are predicted only under certain dynamical conditions: (1) the halo must form with gaseous dissipation, so that gas enriched by outlying massive stars is concentrated inwards before most of the inner stars form; and (2) supernova ejecta must be mixed into the infalling gas on a time scale shorter than that for star formation. The absence of a gradient beyond 20 kpc thus implies either free-fall collapse of the outer halo and/or inefficient mixing during its formation. Conversely, collapse and star formation within 20 kpc were apparently slow enough for mixing and inward concentration to occur; further evidence for a slow collapse in this region comes from the spread of possibly $\sim$ 3 Gyr in the ages of globular clusters within 20 kpc (McClure, this conference).

Further information on the halo collapse comes from the frequency distribution of the metallicities of halo stars, an empirical function to be denoted S(Z). Hartwick (1976) noticed that the halo has too many metal-poor stars to be consistent with the so-called 'simple model': i.e. homogeneous evolution of a closed system with the IMF that holds in the disk. (This is an amusing reversal of the famous G-dwarf problem for disk stars!) Further data by Searle and Zinn (Searle,1977) strengthen this conclusion. Hartwick (1976) showed that the empirical S(Z) could be explained if gas is continually driven out of the regions of star formation, e.g. by supernova heating. Searle (1977) gave an alternative explanation, in which the halo forms as fragments that do not mix with each other and in each of which there was a small number ($\lesssim$ 10) of independent "enrichment events" (several supernovae). It seems plausible that both gas outflow and inhomogeneity may have been effective; supernova ejecta from the halo could have gone partly into enriching the initial disk gas (Ostriker, this conference), and the proto-halo was probably lumpy enough for chemical homogeneity to be unlikely (Larson, this conference).

Yet another possible explanation for the halo S(Z) was noted by Hartwick (1976): the excess of metal-poor stars can be explained even in a simple model if the yield was smaller in the halo than in the disk. Specifically, Searle's (1977) plot of S(Z) requires a factor of 7 reduction in the yield of iron, the element dominating most metallicity indices. For two reasons, at least some reduction seems plausible, without recourse to an ad hoc reduction in the number of massive stars in the halo: (1) According to Schmidt (1975), the halo has a steeper IMF for stars below about 0.7 $M_\odot$ than does the disk; a significantly smaller yield of all elements must therefore prevail in the halo, if the upper IMF and lower mass limit were the same as in the disk. (2) Iron appears to be produced by Type I supernovae, and the positions of these supernovae in galaxies suggest that their stellar precursors would die relatively rarely during the first few times 10^8 yr of star formation in the halo (see §3.3); at least the outer halo stars therefore probably lack a significant source of iron that is available to disk stars. If the last hypothesis accounts for the excess of iron-poor halo stars, then their oxygen abundance distribution should correspond to that in a simple model; and at least, it may be anticipated that the frequency distribution of oxygen abundances in halo stars will show relatively fewer deficient stars than does the "metallicity" distribution based mainly on iron. There are already some indications of oxygen under-deficiency in a few metal-poor stars (Conti et al., 1967;Lambert et al., 1974).

It should be noted that the S(Z) under discussion is for globular clusters, which may not have compositions representative of halo field stars. Information on the radial and frequency distributions of abundances (especially of oxygen) in halo field stars will be very valuable; a survey of oxygen abundances is in progress by J. Laird and D. Butler at Yale University.

2.2 Gradients in the disk

Several speakers at this conference (e.g. Janes, Mayor and Peimbert) have presented data showing that both stars and gas in the disk of the Galaxy have a substantial negative abundance gradient. Two types of dynamical processes could be responsible.

First, a radial gradient in stellar and interstellar abundances will arise if the time scale for conversion to gas to stars increases outwards, since the interstellar and mean stellar abundances in a region increase as the residual gas fraction decreases. Such a time-scale gradient could be due, for example, to a dependence of the star formation efficiency on surface density (Talbot and Arnett, 1975; Chiosi, this conference), or to a radially increasing time scale for the disk to form by gradual infall (Larson, this conference). In this case, the stellar metallicity gradient is expected to be shallower at smaller radii, since the mean stellar Z is insensitive to the residual gas fraction when that is small; Janes (this conference) reports just such a variation in slope of the stellar metallicity gradient with radius.

Secondly, radial inflow of gas in the disk will give rise to an interstellar metallicity gradient (which would be reflected in stellar abundances only if it was effective at early enough times. One can show that the gas metallicity Z_g acquires a gradient $d(Z_g/y)/d \ln R \sim$ ($-$ SFR /inflow rate), where y is the yield. For example, a gradient in the solar vicinity $d[Fe/H]/dR \sim -0.1$, as observed, could be set up by an inward drift of gas at ~ 2.5 km/s. Much faster inflow would rapidly wipe out any gradient in Z_g; circulation currents with time scales $\sim 10^9$ yr (Waxman, this conference) would have the same effect.

An outstanding property of gradients in the galaxy is the gap in gas density and young stars between about 600 pc and 4 kpc from the galactic center, which suggests a gas flow from the inner disk to the central regions (see Roberts' and Sanders' reviews here). If such a flow occurs, chemical evolution near the galactic center would be strongly affected by the inward concentration of elements, and one would expect overabundances in the gas, especially of elements produced by relatively long-lived stars. On the other hand, the galactic center region could be affected by gas outflow, in a supernova-driven wind, which would tend to deplete it of new elements and especially of elements from the envelopes of older stars that are outside the central complex of molecular clouds and HII regions (cf. Audouze, this conference). Perhaps comparisons between the compositions of stars and gas near the galactic center and further out in the disk will eventually provide a test of the types of gas flows that occur; at present, there is too much ambiguity in the abundances themselves, due to problems like chemical fractionation, for a detailed discussion to be made.

2.3 The G dwarf problem

As a final example of how abundances may point to dynamical processes, I consider the present status of the notorious "G dwarf problem" for disk stars in the solar neighborhood: if late G dwarfs are representative of all stars ever formed, there are too few metal-poor stars for the region to be modeled as a closed, homogeneous system with an invariant IMF. (For schematic illustrations, see e.g. van den Bergh [1962] and AT.). Many alternative models have been proposed to account for the disk S(Z), by dropping one or more of the foregoing assumptions. The following five ideas are representative.

(1) The disk may be so old that the late G dwarfs were all formed after most enrichment took place in the disk; the numerous metal-poor stars predicted by the simple model would then be found among K dwarfs (Biermann and Biermann, 1977). A strong empirical argument against this hypothesis is that the HR diagram for stars in the solar neighborhood shows a turnoff at early G, implying that late G dwarfs do sample the whole lifetime of the disk. (2) If the disk gas was always very poorly mixed, and if star formation is favored by a high metallicity (e.g. because oxygen acts as a cooling agent), the proportion of metal-poor stars would be lower than in a homogeneous model (Searle, 1972; Talbor and Arnett, 1973; Talbot, 1974). An extreme efficiency of this process is needed to explain the metallicities of stars formed when the mean Z was very low, if no additional effect (such as the next three) is postulated. (3) A brief initial burst of massive stars may have enriched the disk gas substantially before any long-lived stars formed (Schmidt, 1963; later references in AT). Pagel and Patchett (1975) noted that this process requires the present yield to be several times smaller than predicted by current nucleosysthesis theory, but I believe that the discrepancy is not significant. The best argument against the initial-burst hypothesis is that it is ad hoc - perhaps a weak argument in view of good evidence that IMFs very different from the local disk function do occur, at least on the scale of star clusters (Freemen,1977).

(4) The initial disk gas could have been enriched by supernovae in the halo (Ostriker and Thuan, 1975); this effect is seen in the dynamical models for disk formation discussed by Larson (this conference). (5) If the disk stars formed during infall of metal-poor gas, the present fraction of metal-poor stars would be reduced from the prediction of a closed model in roughly the ratio of initial to final disk mass (Larson, 1972; Tinsley, 1975). Metal-poor infall up to late times is important in the models discussed here by Larson, and in general it is expected if disks form slowly from material that dissipates slowly or falls in from great distances. Moreover, approximately equal rates for star formation and infall are consistent with empirical constraints on both quantities in the solar neighborhood (Cox and Smith, 1976; Tinsley, 1977b).

Again, there are numerous models showing how various solutions to the G dwarf problem would affect other aspects of chemical evolution, and these models suggest some tests as to which solution represents the dominant process. In addition to direct investigations of infall, the effect of metallicity on star formation, etc., there are several tests based on abundances, of which I shall discuss the outlook for two.

Truran (1973) noted that abundance ratios of elements formed in low-mass and massive stars, respectively, would evolve much more slowly with infall than if there was initial enrichment by massive stars. Although the principle of this test is valid, it may be difficult to find suitable pairs of elements. For a clear test, an element must come mainly from stars with lifetimes $\gtrsim 10^9$ yrs ($m \lesssim 2\ M_\odot$), which is not the case for elements produced by typical red giants in the solar neighborhood, since their numbers and envelope ejection are dominated by stars of $> 2\ M_\odot$. For example, recent calculations of CNO processing in stellar envelopes by D. Dearborn (private communication), combined with stellar statistics, indicate that stars above $5\ M_\odot$ are the dominant source of ^{13}C and ^{14}N; the abundance ratios ^{13}C/^{12}C and ^{14}N/^{12}C are therefore predicted to evolve slowly in models with infall <u>or</u> with an initial burst of massive stars (Dearborn, Tinsley, and Schramm, 1978). A similar effect for s-process elements appears in the models described at this conference by Rocca. A further source of confusion is that if an element were to come mainly from stars with lifetims of <u>several</u> billion years, it could increase in abundance relative to a more massive stellar product, even in the most extreme infall model. Altogether, Truran's test for infall vs. initial enrichment can be made only with elements whose sources are firmly established to be in the suitable stellar mass ranges; unfortunately, there are no strong candidates yet.

Another proposed test is based on nucleochronology (Tinsley, 1977b). An early burst of r-process nucleosynthesis would make r-process elements in the early solar system almost as old as the Galaxy itself (4.7 Gyr ago), whereas infall would make the mean age of the elements significantly younger. A comparison between stellar ages and the long-lived radio-isotopes might therefore indicate whether initial enrichment or infall was more important. The validity of this test is called into doubt, however, by the suggestion that most disk stars are no older than the sun (Demarque and McClure, 1977); if so, the aging of elements that entered the solar system reflects an earlier period of galactic history than the formation time of the G dwarfs that motivated the alternative models!

Perhaps a clean choice among model types cannot be made, anyway, because several of the suggested processes may have affected chemical evolution in the solar neighborhood. In particular, dynamical models strongly support the hypotheses that initial enrichment by halo supernovae and later metal-poor infall have occurred. Ultimately the G-dwarf "problem" might become not an enigma but the clearest piece of evidence for drastic effects of dynamics on chemical evolution.

3. RELATED PROBLEMS

In order to use abundances as probes of dynamical evolution, we must have detailed data and a sound understanding of other factors that affect chemical evolution. Some outstanding problems have appeared in the papers and discussions at this Colloquium, of which a few examples are the following.

3.1 Age distribution of stars near the nun

Different authors have quoted significantly different age distributions for nearby disk stars (cf. McClure, Mayor, Grenon), raising the important question of their upper age limit: is the age of NGC 188 (∿ 5 Gyr) an upper bound, as suggested by Demarque and McClure (1977)? If so, then (1) the sun is one of the oldest disk stars, so the solar-system abundance distribution does not reflect the period of galactic evolution during which most nearby stars formed; (2) there was a delay of nearly 10 Gyr between the formation of the halo and a significant disk in this part of the Galaxy; and (3) the correlation between stellar age and metallicity reported here by Mayor conflicts with McClure's null results for open clusters near the sun's distance from the galactic center. The last problem, in particular, would vanish if the metal-poor stars in Mayor's sample are older than NGC 188 and missing from the samples discussed by Demarque and McClure (1977). There could then be a consistent picture of enrichment by a factor ∿ 4 in this part of the disk up to 5 Gyr ago, and very little subsequent enrichment.

3.2 Stellar oxygen abundances

Oxygen is the most abundant of the elements heavier than helium, so it is more directly related than iron to the theoretician's parameter "Z". Moreover, significant production and ejection of oxygen almost certainly occurs only in stars with lifetimes short compared to time scales for galactic evolution, unlike iron and carbon which possibly have sources in stars whose lifetimes exceed the halo collapse time (§3.3). A statistically large set of data on stellar oxygen abundances, as a function of age and position in the Galaxy, would give an important check on many inferences that have been based mainly on iron abundances. An example was discussed in §2.1.

3.3 Type I supernovae (SNI)

About half of all SN in the Galaxy are of Type I, by analogy with external galaxies (Tammann, 1977), so a serious gap in our knowledge of nucleosynthesis arises from ambiguities in the mass range of their precursor stars (Tinsley, 1977a). Kirschner and Oke (1975) have inferred an overabundance of iron in the envelope of one extragalactic SNI, which if typical implies an important contribution to chemical enrichment in iron. Other products of explosive nucleosynthesis might also be ejected by SNI, although observational data are lacking. If SNI come from stars of intermediate mass ($\sim$ 4-8 $M_\odot$), there would be few systematic consequences of the precursor stellar lifetimes relative to more massive stars. However, if the precursor mass range is that of white dwarfs and planetary nebulae ($\lesssim$ 4 $M_\odot$), the composition of most halo stars could show a relative deficiency of any elements contributed by SNI (see §2.1).

It is therefore important that Sneden and Peterson (Sneden, this conference) report essentially solar C/Fe ratios for a sample of unevolved halo stars. The following interpretation is suggested: large carbon overabundances in planetary nebulae (Peimbert, this conference) surely mean that disk stars have a source of carbon that would not have enriched the subdwarfs; therefore, since the solar C/Fe does not exceed the value for subdwarfs, there must also be a low-mass source of iron. An alternative interpretation of Sneden and Peterson's results would be that neither carbon nor iron in the sun has a significant source in low-mass stars, but this is hard to reconcile with the evidence from planetaries. A test of the former hypothesis is obviously to check its prediction that the subdwarfs are relatively oxygen-rich.

3.4 The IMF for O stars

Most chemical enrichment in the Galaxy is believed to be due to stars with initial masses > 10 $M_\odot$ (Arnett, this conference), and these are all O stars, for which both the distribution by spectral type or magnitude and the calibration in terms of mass are extremely uncertain. Problems include the unknown fraction of very short-lived stars that hide within dark clouds (Strom, Strom, and Grasdalen, 1975), the broad range of masses and evolutionary stages corresponding to a given spectral type or luminosity class (e.g. Conti and Burnichan, 1975), and possibly huge effects of inadequate opacities on conventional mass-luminosity relations (Stothers and Chin, 1977). D. Payne of Yale University is considering the distribution of stellar types in the recent O-star catalogue of Cruz-Gonzales et al. (1974), allowing for interstellar absorption; he finds some significant differences from the results of Ostriker et al. (1974) or the simple Salpeter power-law IMF. The problems of completely hidden stars and calibration in terms of mass still remain. Obviously, these uncertainties are an important limitation to the detail with which one can predict chemical evolution.

Related problems are that the slope of the upper IMF may decrease with increasing distance from the galactic center (Burki, 1977), and the upper mass limit may increase outwards (Shields and Tinsley, 1974). These changes would weaken any radial composition gradients arising from the dynamical processes discussed in §2.2 above.

4. CONCLUSION

The Galaxy is too complicated a system for a complete knowledge of its evolution ever to be attained, but there is hope of isolating the most important features. Already, we may understand in broad outline some of the main links between dynamical and chemical evolution. For example, plausible dynamical processes and time scales can be used (with nucleosynthesis theory) to explain why halo stars are metal-poor, why disk stars are metal-rich, and why the disk has an abundance gradient; each of these properties of the Galaxy could be a direct consequence of its formation as a collapsing gas cloud in which stars were forming.

To progress, we need not more models to illustrate relations between possible processes and parameters and their consequences, but more detailed data and physical understanding. Many fundamental and long-standing questions were raised at this meeting, but of course they were still only partially answered. For example: what factors control the star formation rate and IMF? What do stars of various masses eject as they die? What are the present gas flows within, to, and from the Galaxy? What was the mean gas composition and its homogeneity in various elements, at different times and places? Observation and theory have given gradually more detailed answers to these questions since galactic evolution was first studied, while schematic models have explained the main trends and have pointed to fruitful directions for further research. The strong effects that dynamical processes certainly have on chemical evolution imply that studies of stellar and interstellar abundances are probes, not only of nucleosynthesis, but also of the dynamical history of the Galaxy.

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