Chemical Evolution of Galaxies

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ABSTRACT

Chemical evolution of galaxies brings together ideas on stellar evolution and nucleosynthesis with theories of galaxy formation, star formation and galaxy evolution, with all their associated uncertainties. In a new perspective brought about by the Hubble Deep field and follow-up investigations of global star formation rates, diffuse background etc., it has become necessary to consider the chemical composition of dark baryonic matter as well as that of visible matter in galaxies.

Subject headings: galaxies; nucleosynthesis; stellar evolution; abundances

1. Introduction

The seeds of an idea of galactic chemical evolution were planted by Sir Fred Hoyle a long time ago (Hoyle 1946). In the ensuing half century those seeds have grown and proliferated like a cashew-nut tree, with many roots and branches, some firmer than others; but it is not a mature subject in the sense that, say, stellar evolution is, with the basic ideas well understood and steady progress being made on the basis of previous knowledge. There is still a lot of guesswork involved in the physics of star formation, and the very origin of galaxies like our own depends on an as yet unknown balance between monolithic collapse (Eggen, Lynden-Bell & Sandage 1962), accretion of dwarf galaxies (Searle & Zinn 1978), hierarchical clustering (White & Rees 1978), mergers (Toomre 1977), inflows and outflows. These issues were already raised in the classic conference proceedings edited by Tinsley & Larson (1977).

2. Ingredients of chemical evolution models

A chemical evolution model needs to put together at least 5 ingredients:

2.1. Stellar yields

Starting with Arnett (1978) and Renzini & Voli (1981), there have been numerous systematic investigations of stellar element production and ejection, as a function of the initial mass and chemical composition of the star. The broad outlines are clear, but not the details: massive stars explode as core-collapse supernovae, but above some mass limit, which could be of the order of $50M_{\odot}$, the outer layers may fall back into a black hole, reducing or eliminating ejection into the interstellar medium (ISM). Such stars will, however, have ejected significant amounts of helium and carbon at earlier stages in stellar winds (Maeder 1992). Uncertainties arise from the ^{12}C $(\alpha,\gamma)^{16}$O reaction rate, the treatment of convection and mass loss, the explosion mechanism and the mass cut, which is put in by hand to get a Y_e-value appropriate for the observed composition of the iron group (Woosley & Weaver 1995; Thielemann et al. 1996). The bulk of the iron group (say 2/3 in the Solar System) comes, however, from thermonuclear supernovae, Type Ia, consisting of a white dwarf that explodes after accreting matter from a companion (Thielemann et al. 1986). Currently, departures from spherical symmetry are being investigated.

Similar uncertainties apply to intermediate-mass stars, which are responsible for a significant part of nitrogen and ^{13}C and for the main s-process (van den Hoek & Groenewegen 1997; Marigo, Bressan & Chiosi 1998; Gallino et al. 1998).

Talbot & Arnett (1974) introduced the distinction between 'primary' and 'secondary' nucleosynthesis products, according as the yields were insensitive, or sensitive, to the composition of the progenitor star. There is little abundance evidence for 'secondary' behaviour among many elements for which it was once expected (e.g. s-process), but carbon displays secondary-like behaviour, not because of its nuclear progenitors but because higher metallicity favours stronger stellar winds (Gustafsson et al. 1999). Nitrogen, while behaving as a primary element in low-metallicity H II regions, shows a gradually increasing N/O ratio that finally increases even more steeply than a secondary element, because of its dependence on the quasi-secondary carbon (Henry et al. 2000).

2.2. The initial mass function

The overall yield from a generation of stars[1] depends on the initial mass function (IMF), first investigated by Salpeter (1955). Many references to the Salpeter function nowadays refer explicitly or implicitly to a function with the Salpeter slope extending to $0.1M_\odot$ at the low-mass end, which is neither accurate nor any part of what Salpeter originally claimed. While investigations of field stars in the solar neighbourhood have led to significantly steeper functions at the high mass end (Scalo 1986), extragalactic studies almost invariably confirm Salpeter's slope above $1M_\odot$ or so (e.g. Madau et al. 1996). This leads to some intriguing consequences for galactic chemical evolution models, as the full Salpeter function (extending between 0.1 and $100M_\odot$, say) leads to an overall yield around $2Z_\odot$, too high for the solar neighbourhood; modellers using that function then either adopt a still lower low-mass truncation and/or assume an upper limit of $50M_\odot$ or less to stars that become supernovae, more massive stars locking themselves in black holes. The Miller-Scalo and Scalo functions do not need this device, but their lower overall yield has a problem explaining the metallicity of X-ray gas in clusters of galaxies.

Is the IMF invariable? As there is no real theory, the question is wide open, but it is of interest to explore how much can be explained on the basis that it is, apart from random realizations of an underlying universal function. In this spirit, Pagel & Tautvaišienė (1998) have attempted to model the chemical evolution of the Magellanic Clouds on the basis of identical yields to those prevailing in the solar neighbourhood (regardless of what particular combination of stellar yields and IMF is responsible for them), rather than blame their low metallicities on a steeper or more bottom-heavy IMF. Observations tend to favour a universal Salpeter slope above some critical mass below which it flattens or turns over; that critical mass may or may not be variable (Elmegreen 2000).

2.3. Star formation rates

Schmidt (1959) proposed a star formation law depending on a power between 1 and 2 of the volume or surface density of gas; such laws have been used in many models and can give a good account of the distribution of gas density and abundances in the Milky Way (e.g. Matteucci & François 1989), especially when some form of self-regulation is incorporated in the coefficients (Dopita & Ryder 1994) . In dwarf and starburst galaxies, on the other hand, star formation often occurs in sporadic bursts, perhaps involving both negative and positive feedback mechanisms. Kennicutt (1998) has given observational evidence for an overall correlation of star formation rates with the surface density of H I, with a definite threshold of order a few $M_\odot$ pc^{-2} which may be related to dynamical stability criteria, and this idea has been used by Chiappini, Matteucci & Gratton (1997) to account for the hiatus in star formation that appears to have occurred between the formation of the thick and thin disks.

2.4. Stellar populations

One issue that has to be addressed, most notably in modelling the Milky Way, is the relationship between different stellar populations — the halo, the bulge, the thick disk and the thin disk. To what extent have they evolved concurrently, either in space or in time, successively or independently? Partly because of angular momentum considerations (Wyse & Gilmore 1992), opinion has veered away from the older idea of a temporal succession: halo, thick disk, thin disk (Burkert, Truran & Hensler 1992) towards the view that the halo and disks evolved independently, gas lost

[1] Defined as the mass of elements freshly produced and ejected by a generation of stars, divided by the mass remaining as long-lived stars or compact remnants (Searle & Sargent 1972).

from the halo ending up in the bulge or the intergalactic medium. The thick disk is old and preceded the thin one, but with a considerable hiatus (Fuhrmann 1998), either because of the abovementioned threshold effect or because of a merger which led to the thickening of the disk in the first place.

2.5. Interaction with other galaxies and the intergalactic medium

Since the pioneering paper by Larson (1972), it has become clear that inflow of relatively unprocessed material is potentially an important factor, notably in helping to solve the notorious G-dwarf problem (see below), and it was also Larson who developed models of terminal galactic winds to account for the luminosity-metallicity relation and predicted the presence of heavy elements in intracluster gas (Larson & Dinerstein 1975). More recent 'chemo-dynamical' models also take into account the multi-phase structure of the ISM, with stellar ejecta supplying the hot medium and fresh stars forming in the cool one (Samland, Hensler & Theis 1997).

3. What have we learned from observations?

3.1. The G-dwarf problem

Sometimes dismissed as a little local difficulty, the G-dwarf problem (van den Bergh 1962; Schmidt 1963; Pagel & Patchett 1975; Lynden-Bell 1975) has proved to be a severe constraint on chemical evolution models, not only in the solar neighbourhood, but in elliptical galaxies (Bressan et al. 1994; Worthey et al. 1996) and the Magellanic Clouds (Cole et al. 2000) as well. The problem is that in all these cases there is a narrow distribution of metallicity (MDF), whereas naive concepts of chemical evolution lead to the expectation of a broad one. Such a narrow distribution probably helped to hold up the abandonment of the idea of a universal cosmic abundance distribution (cf. Sandage 2000), and it also explains why stellar population synthesis models assuming just a single metallicity (SSPs) have been quite successful — more so than models incorporating chemical evolution up to now. These models are gradually becoming more refined, often with an indication of a bimodal metallicity distribution (Maraston & Thomas 2000), which may be understandable as a consequence of mergers. Closely related to the G-dwarf problem is the lack of a single clear age-metallicity relation in the solar neighbourhood, explainable only in part by the mixing of populations from different galactocentric distances evolving on different time-scales (Edvardsson et al. 1993).

The MDF is broader in the Galactic bulge and broader still in the halo, with an apparently higher yield (at least for α-elements) in the former case and a lower one in the latter, where a modified Simple model assuming outflow actually fits the MDF rather well (Hartwick 1976). If the outflow went into the bulge, that might give an explanation for its higher apparent yield on the lines of the 'concentration model' of Lynden-Bell (1975) and the models of elliptical galaxy formation by Larson (1976). The halo MDF is becoming well known from the heroic efforts of Beers et al. (1998), and it fits the modified Simple model down to about [Fe/H] $\simeq -3$; below that it falls short and below -4 there are 2 stars or less when nearly 10 might have been expected. If significant, this discrepancy could indicate the presence of a distinct Population III of massive stars only, or it could merely be the result of low-mass stars being formed in the neighbourhood of exploding supernovae, for which there is other evidence (see below).

3.2. Abundance patterns

Abundance ratios are a better 'clock' than metallicities themselves (however defined). The 'α-rich' effect (Wallerstein 1962) and the O/Fe enhancement (Gasson & Pagel 1966; Conti et al. 1967) are a steady function of metallicity in the thin disk, reaching more or less a plateau in the thick disk and halo, and attributed to the diminishing contribution of SNIa to the elements in increasingly old stars (Wheeler, Sneden & Truran 1989). There is currently controversy as to whether O/Fe actually has a plateau or rises steadily with diminishing Fe/H (Israelian et al. 1999; Boesgaard et al. 1999; Fulbright & Kraft 1999). Numerical GCE models predict a steeper rise in ratios like [Mg/Fe] than is observed, but this depends on assumptions about SNII yields that may be invalid and the predicted slope is reduced in any case when finite mixing times are taken into account (Thomas, Greggio & Bender

1999). Complications in this pattern have been found in two respects: (i) some halo stars have more solar-like α/Fe ratios than do thick-disk stars and other halo stars at the same Fe/H (Nissen & Schuster 1997), maybe because they came from more slowly evolving dwarf galaxies like the Magellanic Clouds, which show a similar pattern; and (ii) the α-rich pattern persists among thick-disk stars right up to solar metallicity, indicating a fast-evolving 'get rich quick' population, which may extend into the bulge,[2] and a hiatus with no star formation, just delayed iron-group production combined with some dilution of overall metallicity, before the first stars of the thin disk were formed (Fuhrmann 1998; Gratton et al. 2000).

The time-delay model for α/Fe effects comes up against some difficulties in the case of elliptical galaxies, where there is a very well-marked correlation between Mg_2 and velocity dispersion, but a less well marked one for iron features (Worthey, Faber & Gonzales 1992). This should imply a faster star formation time-scale for larger galaxies, which is hard to understand on the basis of either monolithic or hierarchical clustering models (Thomas & Kauffmann 1999).

At very low metallicities like [Fe/H] $\simeq -3$, just where the modified Simple model MDF is breaking down, new abundance patterns emerge, with a large scatter in r/Fe and other ratios, indicating the influence of individual supernovae (Ryan et al. 1996; McWilliam 1997). One bonus from this is the case of CS 22892–052 with low metallicity and enhanced r-process, enabling a credible thorium chronology to be applied (Cowan et al. 1999). The incidence of this scatter is consistent with the view that stars are formed in globular-cluster sized superbubbles of the order of $10^5 M_\odot$, dominated by output from a single supernova ($2M_\odot$ of oxygen) if the oxygen mass fraction in the ISM is under 2×10^{-5}, i.e. 2×10^{-3} of solar. As the metallicity of the ISM increases, the influence of an individual supernova is diluted and there is a semblance of smooth chemical evolution (Tsujimoto, Shigeyama & Yoshii 1999).

[2] The 'get-rich-quick' nature of the M 31 bulge was already noted by Baade (1963), as Rich (2000) has recently reminded us.

4. Metal supply to the intra-cluster medium

Hot X-ray gas in clusters of galaxies has a mean metallicity of the order of -0.4, whether measured in [Fe/H] or [α/H], and the mass of metals is proportional to that of stars in E and S0 galaxies in the cluster (Arnaud et al. 1992). As discussed by Renzini et al. (1993) and Pagel (1997), this requires a large yield of the order of $2Z_\odot$ if the metals are supplied by stars in the galaxies, reminiscent of what comes from the conventional form of the Salpeter IMF, but high compared with the yield of $0.7Z_\odot$ or so required to fit the MDF in the solar neighbourhood (e.g. Pagel & Tautvaišienė 1995). Does this imply a more top-heavy IMF (e.g. Arimoto & Yoshii 1987)? Because of the metallicity-luminosity relation (e.g. Zaritsky, Kennicutt & Huchra 1994) and considerations of cosmic chemical evolution outlined below, I prefer to think of a universal IMF with a high yield, modified by outflow from the smaller galaxies. While an effective blowout due to supernova feedback may be difficult to achieve in medium-sized galaxies as we see them now (MacLow & Ferrara 1999), there are other mechanisms like tides and ram-pressure stripping, and the galaxies that we see today may have been smaller in the past, before being built up by inflow or put together by hierarchical clustering.

5. Cosmic chemical evolution and dark metals

Observations at high red-shifts, both of emission from star-forming galaxies (Madau et al. 1996; Blain et al. 1999) and of absorption lines in Lyman-α systems (Pettini et al. 1999) have led to interesting investigations of cosmic chemical evolution (Pei, Fall & Hauser 1999). These may account for only a fraction of the metals in the universe, however. From Big-bang nucleosynthesis, we believe that the smoothed-out density of baryonic matter is

$$\Omega_b h_{70}^2 \simeq 0.035 \tag{1}$$

(Tytler et al. 2000), a value just consistent within errors with recent deductions from BOOMERANG and MAXIMA MWB observations (Tegmark & Zaldarriaga 2000; Balbi et al. 2000) or possibly even a slight underestimate, whereas the density of stars is only 1/10 as much (Fukugita, Hogan &

Peebles 1998). The remainder could be in the form of diffuse intergalactic gas, low surface-brightness galaxies, MACHOs or something else. For the first two of these, the metal content is certainly an issue. Mushotzky & Loewenstein (1997) have argued that the intergalactic gas dominates, with the same metallicity as the intra-cluster gas, implying a yield of $2.5Z_{\odot}$, while numerical simulations by Cen & Ostriker (1999) imply a somewhat lower metallicity like $0.1Z_{\odot}$ requiring a yield of about $1.5Z_{\odot}$ (cf. Pagel 1999); thus half or more of the heavy elements in the universe are as yet unseen, although there is a hint of their presence in recent FUSE observations of O VI (Tripp et al. 2000). Models of cosmic chemical evolution disregard the silent majority of dark metals at their peril!

REFERENCES

Arimoto, N. & Yoshii, Y. 1987, A&A, 173, 23

Arnaud, M. et al. 1992, A&A, 254, 49

Arnett, W.D. 1978, ApJ, 219, 1008

Baade, W., C. Payne-Gaposchkin (ed.), 1963, Evolution of Stars and Galaxies, Harvard University Press, p. 256

Balbi, A., Ade, P., Bock, J. et al. 2000, astro-ph/0005124, subm. ApJ

Beers, T.C. et al., in N. Prantzos et al. (eds.), Primordial Nuclei and their Galactic Evolution, Sp. Sci. Rev., 84, 139

Blain, A., Smail, I., Ivison, R.J. & Kneib, J.P. 1999, MNRAS, 302, 632

Boesgaard, A., King, J.R., Deliyannis, C.P. & Vogt, S.S. 1999, AJ, 117, 492

Bressan, A., Chiosi, C. & Fagotto, F. 1994, ApJS, 94, 63

Burkert, A., Truran, J.W. & Hensler, G. 1992, ApJ, 391, 651

Cen, R. & Ostriker, J.P. 1999, ApJ, 514, 1

Chiappini, C., Matteucci, F. & Gratton, R. 1997, ApJ, 477, 765

Cole, A.A., Smecker-Hane, T.A. & Gallagher, J.S. III 2000, AJ, in press, astro-ph/0006327

Conti, P.S., Greenstein, J.L., Spinrad, H., Wallerstein, G. & Vardya, M.S. 1967, ApJ, 148, 105

Cowan, J.J. et al. 1999, ApJ, 521, 194

Dopita, M.A. & Ryder, S.D. 1994, ApJ, 430, 163

Edvardsson, B., Andersen, J., Gustafsson, B. , Lambert, D.L., Nissen, P.E. & Tomkin, J. et al. 1993, A&A, 275, 101

Eggen, O.J., Lynden-Bell, D. & Sandage, A.R. 1962, ApJ, 136, 748

Elmegreen, B.G. 2000, ESA SP-445, in press, astro-ph/0005189

Fuhrmann, K. 1998, A&A, 338, 161

Fukugita, M., Hogan, C.J. & Peebles, P.J.E. 1998, ApJ, 503, 518

Fulbright, J.P. & Kraft, R.P. 1999, AJ, 118, 527

Gallino, R. et al. 1998, ApJ, 497, 388

Gasson, R.E.M. & Pagel, B.E.J. 1966, Observatory, 86, 196

Gratton, R., Carretta, E., Matteucci, F. & Sneden, C. 2000, A&A, in press, astro-ph/0004157

Gustafsson, B., Karlsson, T., Olsson, E., Edvardsson, B. & Ryde, N. 1999, A&A, 342, 426

Hartwick, F.D.A. 1976, ApJ, 209, 418

Henry, R.B.C., Edmunds, M.G. & Koeppen, J. 2000, ApJ, in press, astro-ph/0004299

Hoyle, F. 1946, MNRAS, 106, 343

Israelian, G., García Lopez, R.J. & Rebolo, R. 1998, ApJ, 507, 805

Kennicutt, R.C. 1998, ApJ, 498, 541

Larson, R.B. 1972, Nature Phys. Sci., 236, 7

Larson, R.B. 1976, MNRAS, 176, 31

Larson, R.B. & Dinerstein, H. 1975, PASP, 87, 911

Lynden-Bell, D. 1975, Vistas in Astronomy, 19, 299

MacLow, M.-M. & Ferrara, A. 1999, ApJ, 513, 142

McWilliam, A. 1997, ARA&A, 35, 503

Madau, P., Ferguson, H.C., Dickinson, M.E. et al. 1996, MNRAS, 283, 1388

Maeder, A. 1992, A&A, 264, 105

Maraston, C. & Thomas, D. 2000, ApJ, in press, astro-ph/0004145

Marigo, P., Bressan, A. & Chiosi, C. 1998, A&A, 331, 564

Matteucci, F. & François, P. 1989, MNRAS, 239, 885

Mushotzky, R.F. & Loewenstein, M. 1997, ApJ, 481, L63

Nissen, P.E. & Schuster, W.A. 1997, A&A, 326, 751

Pagel, B.E.J. 1997, Nucleosynthesis and Chemical Evolution of Galaxies, Cambridge University Press

Pagel, B.E.J. 1999, in Ringberg Workshop: *Galaxies in the Young Universe II*, Hans Hippelein (ed.), Springer-Verlag, in press; astro-ph/9911204

Pagel, B.E.J. & Patchett, B.E. 1975, MNRAS, 172, 13

Pagel, B.E.J. & Tautvaišienė, G. 1995, MNRAS, 276, 505

Pagel, B.E.J. & Tautvaišienė, G. 1998, MNRAS, 288, 108

Pei, Y.C., Fall, M. & Hauser, M.G. 1999, ApJ, 522, 604

Pettini, M., Ellison, S.L., Steidel, C.C. et al. 1999, preprint astro-ph/9910131, ApJ, in press

Renzini, A., Ciotti, L., D'Ercole, A. & Pellegrini, S. 1993, ApJ, 419, 52

Renzini, A. & Voli, M. 1981, A&A, 94, 175

Rich, R.M. 2000, in J. Bergeron & A. Renzini (eds.), From Extrasolar Planets to Cosmology: The VLT Opening Symposium, Springer-Verlag, p. 275

Ryan, S., Norris, J. & Beers, T.C. 1996, ApJ, 471, 254

Salpeter, E.E. 1955, ApJ, 121, 161

Samland, M., Hensler, G. & Theis, Ch. 1997, ApJ, 476, 544

Sandage, A.R. 2000, PASP, 112, 293

Scalo, J. 1986, Fund. Cosm. Phys., 11, 1

Schmidt, M. 1959, ApJ, 129, 243

Schmidt, M. 1963, ApJ, 137, 758

Searle, L. & Sargent, W.L.W. 1972, ApJ, 173, 25

Searle, L. & Zinn, R. 1978, ApJ, 225, 357

Talbot, R.J. & Arnett, W.D. 1974, ApJ, 190, 605

Tegmark, M. & Zaldarriaga, M. 2000, Phys. Rev. Lett., in press, astro-ph/0004393

Thielemann, F.-K., Nomoto, K'I. & Hashimoto, M. 1996, ApJ, 460, 408

Thielemann, F.-K., Nomoto, K'I. & Yokoi, K. 1986, A&A, 158, 17

Thomas, D., Greggio, L. & Bender, R. 1999, MNRAS, 302, 537

Thomas, D. & Kauffmann, G. 1999, in *Spectrophotometric Dating of Stars and Galaxies*, I. Hubeny et al. (eds.), ASP Conf. Series, p. 261

Tinsley, B.M. & Larson, R.B. (eds.) 1977, The Evolution of Galaxies and Stellar Populations, Yale University Press

Toomre, A., in B.M. Tinsley & R.B. Larson (eds.), The Evolution of Galaxies and Stellar Populations, Yale University Press, p. 401

Tripp, T.M., Savage, B.D., & Jenkins, E.B. 2000, ApJ, 534, L1

Tsujimoto, T., Shigeyama, & Yoshii, Y. 1999, ApJ, 519, L63

Tytler, D., O'Meara, J.M., Suzuki, N. & Lubin, D. 2000, Physica Scripta, in press, astro-ph/0001318

van den Bergh, S. 1962, AJ, 67, 486

van den Hoek, L.B. & Groenewegen, M.A.T. 1997, A&AS, 123, 305

Wallerstein, G. 1962, ApJS, 5, 1

Wheeler, J.C., Sneden, C. & Truran, J.W. 1989, ARA&A, 27, 279

White, S.D.M. & Rees, M.J. 1978, MNRAS, 183, 341

Woosley, S.E. & Weaver, T.A. 1995, ApJS, 101, 181

Worthey, G., Dorman, B. & Jones, L.A. 1996, AJ, 112, 948

Worthey, G., Faber, S.M. & Gonzalez, J.J. 1992, ApJ, 398, 69

Wyse, R.F.G. & Gilmore, G. 1992, AJ, 104, 144

Zaritsky, D., Kennicutt, R.C. jr & Huchra, J.P. 1994, ApJ, 420, 87