An Empirical View to the Early Chemical Evolution of Bulge/Disk Galaxies

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Abstract. Scaling from the empirical metal yield as measured in clusters of galaxies, it is inferred that early in the evolution of the Galaxy the bulge stellar population has produced $\sim 10^9 M_\odot$ of metals, at least 5 times more than the total metal content of the bulge today. It is argued that an early galactic wind from the starbursting bulge has pre-enriched a vast region around it, with these metals being able to enrich to $\sim 1/10$ solar of order of $5 \times 10^{11} M_\odot$ of pristine material. From the empirical evidence that bulges come before disks, it is inferred that the Milky Way disk formed out of this pre-enriched material, which accounts for the scarcity of metal poor stars in the solar neighborhood, the so-called ‘G-Dwarf Problem’. High redshift observations are now becoming able to efficiently explore the $1.2 < z < 3$ region of the universe, when disk formation and morphological differentiation may have taken place.

1. Introduction

The chemical evolution of the solar neighborhood, as a prototype of galactic disks in general, has been an active field of astrophysical research over the last four decades, starting from the pioneering works of van den Bergh (1962), Schmidt (1963), and Pagel & Patchett (1975). With Talbot & Arnett (1971) and then Tinsley (1980), the subject got its elegant physico-mathematical formulation, then adopted in most later works. In this traditional approach chemical evolution is rigorously treated from first principles, adopting specific initial and boundary conditions, along with heavy element yields obtained from theoretical stellar model and supernova explosion calculations.

In this paper I instead adopt a purely phenomenological approach, lining up a series of observational facts and then building on them semi-quantitative inferences. This should be regarded as complementary to the traditional approach, and may perhaps drive it towards unexplored regions of the theoretical parameter space. I also adopt a ‘simple minded’ attitude, assuming – when appropriate – that the most straightforward interpretation of the facts is the right one, and no cosmic conspiracies are at work (for example, it is subintended that the IMF is universal). For conciseness the presentation will be somewhat schematic.
2. Learning from Clusters of Galaxies

Clusters are perhaps the best realization in nature of the closed-box model of chemical evolution. Within clusters we find confined in the same place all the dark matter, all the baryons, all the galaxies, all the stars and all the metals, that have participated in the play. Clusters are then good archives of their past star formation (SF) and metal production history. X-ray observations of clusters provide iron and α-element abundances in the ICM, along with the ICM mass. Optical observations provide the luminosity, mass, and the average metallicity of all the stars now locked inside galaxies (and even hints to a trace population of intergalactic, free-floating stars). Optical and near-IR observations of cluster elliptical galaxies have also set tight limits to the formation epoch of the bulk of the stars contained in them. Cumulatively, these observations have then established the following facts (see Renzini 1997, 1999a,b and extensive references therein for the original sources):

- The average iron abundance in the ICM is $Z_{\text{Fe}}^\text{ICM} = (0.3 \pm 0.1)Z_{\odot}^\text{Fe}$.
- ICM iron mass to light ratio is $M_{\text{Fe}}^\text{ICM}/L_B = 0.02 \pm 0.01 (M_\odot/L_\odot)$, where $M_{\text{Fe}}^\text{ICM} = Z_{\text{Fe}}^\text{ICM} \times M_\text{ICM}$, $M_\text{ICM}$ is the mass of the ICM, and $L_B$ the total $B$-band luminosity of all cluster galaxies.
- The average iron abundance of cluster stars is roughly solar.
- The total iron mass to light ratio is $(M_{\text{Fe}}^\star + M_{\text{Fe}}^\text{ICM})/L_B = 0.03 \pm 0.01 (M_\odot/L_\odot)$, only weakly dependent on the Hubble constant.
- The global elemental ratio $[\alpha/\text{Fe}]$ in the ICM+stars is roughly solar, hence the total cluster metal mass to light ratio is $M_Z/L_B = 0.3 \pm 0.1 (M_\odot/L_\odot)$, since in solar proportions $Z \simeq 10 \times Z_{\text{Fe}}^\odot$. This is a fully empirical estimate of the metal yield of a now old stellar population.
- Most metals are out of galaxies: $M_{\text{Fe}}^\text{ICM}/M_{\text{Fe}}^\star \simeq 1.6 h^{-3/2}$, i.e. there is $\sim 2.5$ times more iron in the ICM than there is iron locked into stars, for $H_0 = 75$, or $\sim 4.5$ times more for $H_0 = 50$.
- Massive starbursts promote major, metal-enriched galactic winds (Heckman et al. 2000).
- Most stars in galaxy clusters belong to galactic spheroids (ellipticals and bulges), and formed in massive starbursts at $z \gtrsim 3$.

Note that in $M_Z/L_B$ both quantities are measured now; however, the metal mass $M_Z$ was produced and released at very early times by the stellar population that after aging for $\sim 13$ Gyr has faded to the luminosity $L_B$. In the adopted ‘simple-minded’ approach, from these empirical facts the following inferences can be drawn:

- Most metals in clusters (now partly in the ICM, partly in stars) were produced at $z \gtrsim 3$.
- ICM metals were ejected by starburst driven galactic winds at the production time, i.e. at $z \gtrsim 3$. 
3. Field vs Clusters

To which extent are clusters *fair samples* of the universe as a whole? They are certainly the highest density peaks in the distribution of matter, both dark and shining, and one may expect SF and chemical evolution to have proceeded differently in clusters compared to the low-density *field*. However, there are also striking similarities, including the following ones:

- Most stars are now in galactic spheroids, in the field as in the clusters (e.g. up to $\sim 75\%$ according to Fukugita, Hogan, & Peebles 1998).
- The Fraction of baryons now locked into stars is nearly independent of the environment, being $\sim 10\%$ in both clusters and field (e.g. Renzini 1997; Fukugita et al. 1998). The SF histories may well have been different, confined at early times in clusters, more protracted in the field, but the $z = 0$ endproducts appear to be very similar, with nearly the same efficiency of baryon to star conversion.
- Field ellipticals and S0’s are very similar to cluster ellipticals and S0’s, with the luminosity-weighed age of their stellar populations being at most $\sim 1$ Gyr less than that of the cluster galaxies (Bernardi et al. 1998).
- The stellar populations of (large) bulges are very similar to ellipticals. The majority of them appear to follow the same $\text{Mg}_2 - \sigma$ relation of ellipticals, while a minority of outliers likely had a significant episode of star SF at later times (Jablonka, Martin, & Arimoto 1996).
- The stellar population of the Galactic bulge is nearly as old as Galactic globular clusters in halo, or 13-15 Gyr (Ortolani et al. 1995).

Again, from this second series of facts more ‘simple-minded’ inferences can be drawn:

- Having the SF proceeded to the same $\sim 10\%$ baryon to stars conversion in the general field and in clusters, the global metallicity of the $z = 0$ universe has to be nearly the same as that we can actually see in clusters, i.e. $\sim 1/3$ solar.
- The bulk of stars in galactic spheroids – in clusters as well as in the field – formed at $z \gtrsim 3$.
- Since some 50 to 75% of all stars are now in spheroid, and the bulk of stars in spheroids formed at $z \gtrsim 3$, the inference is that at least $\sim 1/3$ of all stars formed at $z \gtrsim 3$. This ‘fossil evidence’ argument agrees with the direct determination of the SF history at high redshift (Steidel et al. 1999).
- Therefore, the metallicity of the $z = 3$ universe was $\sim 1/3$ of its present value, i.e. $\sim 1/3 \cdot 1/3 \simeq 1/10$ solar, a *prompt initial enrichment of the universe* (Renzini 1999a).

4. Bulges vs Disks

When did the morphological differentiation of galaxies take place? When did the disks of the present-day spirals started to be assembled? Here are some facts:

- We see no disk galaxies at $z \gtrsim 3$. Lyman break galaxies appear to be much smaller, compact objects, most likely the progenitors of today’s objects that
the fossil evidence date having formed at $z \gtrsim 3$, i.e. galactic spheroids (e.g. Giavalisco, Steidel, & Macchetto 1996).

• Spirals are well in place by $z = 1$, along with passively evolving ellipticals (e.g. Abraham & van den Bergh 2001).

Hence:

• Bulges come first, formed in starbursts, and disks are slowly added later, if the environment is quiet enough to allow for their formation and survival.

• The morphological differentiation of galaxies (the emergence of the Hubble sequence) took place between $z \sim 3$ and $z \sim 1$, i.e. in the so far poorly explored desert range $1 < z < 3$.

5. The Early Chemical Evolution of the Milky Way

In the K band the Galactic bulge and disk contribute respectively $\sim 1.2 \times 10^{10}$ and $\sim 5.5 \times 10^{10} L_{K,\odot}$ (Kent, Dame, & Fazio 1991), and in the B band the bulge luminosity is $L_{B,\text{BULGE}} \simeq 6 \times 10^9 L_{B,\odot}$.

From the cluster empirical yield it follows that the Galactic bulge has produced $M_Z \simeq 0.3 L_{B,\text{BULGE}} = 0.3 \times 6 \times 10^9 \simeq 2 \times 10^9 M_{\odot}$ of metals. Where are all these metals? Two billion solar masses of metals should not be easy to hide, yet ... The stellar mass of the bulge follows from its $K$-band mass to light ratio, $M_{B,\text{BULGE}}^* / L_K = 1$ (Kent 1992), and its luminosity, hence $M_{B,\text{BULGE}} \simeq 10^{10} M_{\odot}$.

Its average metallicity is about solar (McWilliam & Rich 1994), i.e. $Z = 0.02$, and therefore the bulge stars all together contain $\sim 2 \times 10^8 M_{\odot}$ of metals. Only $\sim 1/10$ of the metals produced when the bulge was actively star forming some 13 Gyr ago are still in the bulge! This implies that $\sim 90\%$, or $\sim 1.8 \times 10^9 M_{\odot}$ were ejected into the surrounding space by an early wind.

A word of caution is in order. The estimated the metal yield (Section 2) follows from adopting $Z_{\text{ICM}} = 0.3$ solar. More recent estimates prefer $Z_{\text{ICM}} = 0.2$ solar (De Grandi & Molendi 2001), the total metal production by the bulge reduces to $\sim 1.3 \times 10^9 M_{\odot}$, of which $\sim 10^9 M_{\odot}$ had to be ejected. The bottom line is that at least 5 times more metals were ejected, than retained in the bulge.

At the time of bulge formation, such $\sim 10^9 M_{\odot}$ of metals run into largely pristine ($Z = 0$) material, experienced R-T instabilities leading to chaotic mixing, and establishing a distribution of metallicities in a largely inhomogeneous IGM surrounding the young bulge. For example, this enormous amount of metals is able to bring to a metallicity $1/10$ solar (i.e. $Z = 0.002$) about $5 \times 10^{11} M_{\odot}$ of pristine material, several times the mass of the yet to be formed Galactic disk.

5.1. Three Phases in the Milky Way Build Up

If we look to the formation of the Milky Way galaxy from a purely empirical point of view, we have an old, now passively evolving bulge, and a younger disk, still forming stars even if – likely – at a reduced rate compared to a more active past. Hence, we can distinguish three main phases in the formation and evolution of our own Galaxy.
Phase 1: Bulge Formation, some 13 Gyr ago ("at $z \sim 3$"). The relatively fast ($\lesssim 1$ Gyr) assembly of the bulge from smaller subunits promotes a massive starburst (SFR=$10$-$100$ $M_\odot$/yr), which drives a metal rich wind and $\sim 10^9 M_\odot$ of metals are ejected into the surrounding medium.

Phase 2: The Intermission, lasting a poorly constrained lapse of time (some Gyr?, until $z \sim 2.5$?), during which the bulge settles into its passive evolution, the ejecta partially mix with the surrounding medium, and a mass some 5-10 times larger than the present mass of the Galaxy is inhomogeneously contaminated, with its average metallicity being raised to $\sim 1/10$ solar. Heating of this metal enriched environment (MEE) by the early bulge wind, may prevent from a while further growth of the stellar mass of the protogalaxy.

Phase 3: Disk Formation, from $z \sim 2.5$ to $z \sim 1$ (?). Around the aging bulge, the MEE is cooling, infall starts of $Z \simeq 1/10$ solar material from the MEE, and the Galactic disk begins to form and grow.

6. Conclusions

These semi-quantitative arguments may help settling on a final solution for an old problem. From the earliest times mentioned in the Introduction, the existence of a “G-Dwarf Problem” was soon recognized: the solar neighborhood contains far too few metal poor stars ($z < 1/10$ solar) compared to the prediction of a simple, closed box model of chemical evolution (see Pagel 2001, for a recent discussion of the problem). Traditional solutions of the G-Dwarf problem have considered three options (or some combination of them): an initial top heavy IMF, a prompt initial enrichment (PIE) model, and infall, i.e. the gradual assembly of the disk as opposed to a zero metallicity disk fully assembled from the beginning. The above considerations clearly indicate that PIE is inevitable, once one accepts that the bulge comes first and the disk later. Note that infall models have often assumed $Z = 0$ for the infalling material. Some gradual growth of the disk is also inevitable, being the alternative assumption of instantly assembled disk quite unrealistic. So, a combination of PIE and infall emerges as the natural solution of the old problem. Worth mentioning here is that the idea of the bulge pre-enriching the disk is certainly not new (see e.g. Köppen & Arimoto 1990).

This sketchy cartoon of galaxy formation is hard to put in more quantitative terms, purely from first principles. Models would have difficulties to predict the extension of the MEE, its distribution of metallicities, the duration of the intermission, the evolution of the infall rate and the disk build up. All these phenomena involve highly non-linear, weather-like hydrodynamics with little predictive power. However, we are living in a special time for astronomy, and where theory gets stuck observations can help. We can actually start to see directly what theory is not able to predict.

With the current generation of large ground based telescopes, together with the X-ray, optical, and infrared facilities now or soon in space, we have for the first time the possibility to empirically map the growth of galaxies, to follow back in time the disappearance of the Hubble sequence, and its emergence, forwards from high to low redshifts.
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