Starbursts and their contribution
to metal enrichment

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I review the properties of Starburst galaxies, compare the properties of the local ones with more distant starbursts and examine their role in the metal enrichment of the interstellar medium and the intergalactic-intracluster medium. Metallicity is not an arrow of time and contrary to current belief metal rich galaxies can also be found at high redshift.

1. Introduction

For the purpose of this conference, let me first stress that known starburst galaxies in the local universe are not metal rich (Z ≤ Z⊙). Having written this, I remark however that ’metal-rich’ has different acceptance depending upon one’s field of interest. Stellar astrophysicists deal with individual stars as metal poor as [X] ≈ −4 similar or quite to some DLAs, hence they would regard solar abundances as being large! On the other hand, the most dramatic case known, so far, of metal overabundance comes from QSOs spectroscopy with [N/H] ≈ 1 (Hamann et al. 2002). Most of my talk will review our knowledge about local starbursts. While starburst galaxies are not known to be metal rich objects they fit nevertheless with this meeting. They are particularly interesting in their own right, while bearing very strong similarities with their high redshift counterparts, because they are very significant components of our present-day universe and mostly important sources of chemical enrichment. Moreover, their study, brings the important clue that metallicity is not providing us with an arrow of time, as is too often believed. Moreover, high redshift galaxies that are obscured and with high star formation rates can be even more metal rich than their low luminosity analogs of the Local Universe.

2. Phenomenology and Definitions

The concept of ”starburst” sometimes leads to confusion. A starburst ”event” refers to the formation of thousands of massive stars (M⊙ ≥ 20) on a very small volume (few pc) and a time scale of only a few million years (Hoyos 2006). Such an event may occur in a normal galaxy such as our Galaxy or 30 Dor in the LMC. At variance, a starburst galaxy displays violent star formation on such a scale that the whole system is out of balance with respect to available resources. Perhaps the most fundamental definition of a starburst would be a galaxy in which the star-formation rate approaches the upper limit set by causality (Heckman, 2005, his Fig. 1). For a given total mass and gas mass fraction the upper bound of the star formation rate (SFR) is proportional to σ^4 where σ is the stellar velocity dispersion (Murray et al. 2005). Other physical quantities are often considered such as the duration at which the current SFR consumes the remaining interstellar gas (the inverse of this is called the efficiency). In such context, a starburst produces the current stellar mass at the observed star formation rate on a time much shorter than a Hubble time. As pointed out by Kennicutt (1998) a starburst must develop a large SFR per unit area. Extreme starbursts have star formation rates per unit area larger than 1M⊙ yr⁻¹ kpc⁻². These figures correspond to L(bol) ≥ 10^{10}L⊙ kpc⁻² hence thousands of times larger than normal discs galaxies and consumption times of only 10^8
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years. It is important to realize that this definition refers to major starbursts and is somewhat arbitrary: starburst properties appear mostly continuous across the range of amplitudes observed.

3. The Local Star-Forming Galaxies

Local Star-Forming galaxies provide roughly 10% of the total radiated energy and roughly 20% of all the high mass star formation in the present day (Brinchmann et al. 2004). Among local star forming galaxies, sometimes referred as HII galaxies, most are dwarfs: dwarf irregulars (dIrr) and Blue Compact Dwarfs (BCD). They remain, however, a minority among the general population of dwarf galaxies (Kunth & Ośtlin, 2000; hereafter KO2000). In term of absolute star formation rates most figures are not very impressive. Dwarfs range from $M_B \approx -14.0$ to -17.0 and SFRs from $\approx 0.02$ to $1 \, M_{\odot} \, yr^{-1}$, while giants have $M_B$ up to -21 and reach SFRs of 20 to $40 \, M_{\odot} \, yr^{-1}$ at most. These galaxies possess a gigantic reservoir of HI gas that sometimes extends into huge halos surrounding the optical region. The mechanism that ignites strong bursts of star formation across these systems is still not clear. Star formation may be triggered during encounter events (merging or interacting galaxies) or stochastic processes within the galaxy itself.

At optical wavelengths, their spectra are dominated by young stars and ionised gas, closely resembling those of giant HII regions in nearby spiral and irregular galaxies. Analysis of their spectra show that most of them are metal deficient. Towards the lower end of the metallicity distribution ($O/H \sim 1/50 \, Z_\odot$) we find galaxies like IZw18 and SBS0335-052. Due to their extreme properties it has been conjectured by Searle & Sargent (1970) that these chemically unevolved galaxies could be young systems still in the process of forming.

In star forming dwarfs, because of their low mass, star formation event occurs over a large part of the discs. Some star forming regions are very compact and remain confined within the inner few hundreds pc of their hosts while others have one or several star forming clumps in off–nucleus regions. These events have strong and sometimes devastating impact on their different phases of the interstellar medium. The hot gas, typically observed in X-rays, can, at least in some cases, blow out from these galaxies (see Section 8). A starburst event is likely to provide an important mechanism for the metal enrichment of the intergalactic medium (IGM) in the early universe. On small scales, some dwarf galaxies show numerous HI holes, suggesting propagating star formation and allowing the investigation of early phases of what later may become a blow-out of the gas. Molecular gas, the site of actual star formation, is notoriously difficult to detect in dwarfs. The reasons for this are not necessarily related to a dearth of molecular material, but rather the low metallicity environment characteristic for dwarf galaxies and the low HI density that inhibit the rate of formation of the diffuse molecular gas. It is also likely that the diffuse molecular hydrogen is destroyed by the incident UV flux from the massive stars in the star-forming region. Most of the remaining molecules should be in dense clumps, which are opaque to far-UV radiation, and do not contribute to the observed spectra (Vidal-Madjar et al. 2000; Hoopes et al. 2004).

4. The more distant starbursts

At $0.4 \leq z \leq 1.0$ Luminous Compact Blue Galaxies (LCBGs) dominate the number density of galaxies at intermediate redshifts. They are small starburst systems of ($R_e \leq 3.0$ kpc) that have evolved more than any other galaxy class in the last 8 Gyrs (Philipps et al. 1997, Guzman et al. 2003). They are a major contributor to the observed enhancement
of the UV luminosity density of the universe at $z < 1$, their number density decline being in concert with the rapid drop in the global Star Formation Rate since $z = 1$. They appear to form a bridge in redshift, size, and luminosity between Lyman-break galaxies and local HII galaxies today. On the other hand, the work of Steidel and collaborators (e.g. Steidel et al. 1996) has confirmed a substantial population of star-forming galaxies at $z \sim 3$, with a comoving number density of roughly 10 to 50% that of present day luminous galaxies ($L \geq L^*$). It is clear that observational biases play a role since at $z \geq 2$, $L \leq L^*$ are more difficult to study.

5. Measuring heavy element abundances from ionized gas

The spectral analysis of the HII galaxies shows that many HII galaxies are metal poor objects (probably the reason I was invited to speak at this conference!), some of them – I Zw18 and SBS 0335-052 – being among the most metal poor systems known. Heavy element abundances are relatively easy to measure in star-forming galaxies because they contain ionized gas clouds in which large numbers of hot stars are embedded. What is observed in the optical are narrow emission lines superimposed on a blue stellar continuum. These are identified as helium and hydrogen recombination lines and several forbidden lines: O, N, S, Ne, Ar, H and He lines are currently measured (Izotov et al., 2006). Methods used in determining abundances are well understood and generally more reliable than those based on stellar absorption line data because transfer problems become less important.

Oxygen is the most reliably determined element, since the major ionisation stages can all be observed. Moreover the $[\text{OIII}]\lambda 4363$ line allows an accurate determination of the electron temperature. The intrinsic uncertainty in this method is of the order of $\sim 0.1$ dex. Furthermore, when the electron temperature cannot be determined, empirical relations between the oxygen abundance and the $[\text{OII}]\lambda 3727$ and $[\text{OIII}]\lambda\lambda 4959, 5007$ strength relative to H$\beta$ are used, though with lower accuracy (0.2 dex or worse), (Pagel, 1997). For other species, in general, all the ionisation stages are not seen and an ionisation correction factor must be applied to derive their total abundances.

The ultraviolet (UV) region is dominated by the hot stellar continuum and shows relatively weak emission lines except for those that originate in stellar winds and has provided ways of measuring nebular carbon and silicon abundances.

We caution that many parameters control the observed metallicity in a given galaxy. They are incorporated into chemical evolutionary models and include: stellar evolution and nucleosynthesis, inflows and outflows and the problem of the mixing and dispersion time scale of freshly released heavy elements (KO2000). Moreover, metallicity measurements may be relevant to only one particular component of a galaxy. A suggestion of Kunth & Sargent (1986) has been made that HII gas could enrich itself with metals expelled by CC-SNe of time scales shorter than the lifetime of a starburst (self-pollution). Recent FUSE observations of some dwarf galaxies show a possible disconnect in metallicity between HI and HII regions, although possible saturation effects on the line of sight may alter such a comparison (Lebouteiller et al. 2006).

One important aspect of HII regions abundances is that they can be obtained also at great distances. This makes them powerful tools also for studying high redshift galaxies, with the price that our view will be biased towards actively star-forming systems. For a discussion on possible problems associated with deriving abundances in very distant galaxies, see Kobulnicky et al. (1999).
5.1. Do we expect metal-rich systems?

Knowledge of the chemical composition could be used to constrain the age of any given galaxy provided that the heavy element abundance of galaxies increases forever with age, and that the gas-phase metallicity can be assumed to be equal to the metal abundance of the stellar population. The first assumption assumes that galaxies evolve in a “closed box” manner. In this model, the metal content of a galaxy should be a function of its gas mass fraction only. The predicting power of this model would therefore be enormous, should this hypothesis be true for at least some fraction of galaxies (but see Section 7).

One can easily show - under the hypothesis of a Salpeter initial mass function and normal stellar yields that a natural limit would be reached of the order of $\approx 2Z_\odot$. To go beyond this one would need to strongly bias the IMF towards high masses or/and use up all the gas (100% efficiency!). However, galaxies (and star-forming ones in particular) are not known to deviate significantly from normal IMF while they are known to exchange large amounts of gas with the intergalactic medium (outflows, infall, merging etc.). Hence it can be understood that the requirements applying to the cosmic enrichment of the Universe as a whole are not always met for individual galaxies. One can of course argue that observationally very metal rich galaxies might escape from emission line surveys as their usual tracers such as the $\lambda\lambda 4959, 5007$, for instance, become extremely faint beyond $12+\log(O/H)= 9.0$ (Stasinska, 2002).

The second requirement is more complex to verify. First of all the gas-phase metallicity does not necessarily directly relate to the heavy-element abundance of a galaxy. Second, it is very important to keep in mind that metals ejected from dying stars do not necessarily mix instantly into the general interstellar medium of galaxies (Roy & Kunth, 1995). This delay can be as large as one billion years (Tenorio-Tagle, 1996). This point is further discussed in Section 8.

6. The Luminosity-Metallicity relation

Star-forming galaxies will likely produce superwinds that will export metal-enriched gas to the intergalactic medium. Merger events will also disrupt the “closed-box” model paradigm. The strongest evidence from a departure from simple close box models comes from the luminosity-metallicity relation. The luminosity–metallicity relationship, in such a context, is a useful relationship between evolutionary state and metallicity hence the location of galaxies in the $M_B-12+\log(O/H)$ plane is of crucial importance to understand the details of the inner workings of starbursts. One reason for the existence of this relationship - assuming that more luminous galaxies are also more massive - is that more massive objects can lock up the metals created in their stars more easily than less massive galaxies because of their deeper gravitational wells. A metallicity luminosity relation can also arise if smaller galaxies have larger gas fractions than larger galaxies. This is seen statistically in the local universe and can result from the fact that smaller galaxies evolve more slowly (lower SFR per unit gas mass) than larger ones. In Fig. 1, we show the oxygen abundance vs. luminosity diagram for dIs (crosses), BCGs (filled symbols) and LSBGs (open symbols), based on data collected from the literature, with available abundances and integrated B magnitudes. At first sight many BCGs do not appear extreme when compared to the normal dIs. Indeed some BCGs are more metal rich than dIs at a given luminosity, while the opposite would be expected if BCGs were bursting dIs. These BCGs may be in a post burst stage and the fresh metals may have become “visible” already. Secondly, some “extreme BCGs” appear much more metal-poor at a given luminosity. These extreme BCGs (XBCGs as listed in KO2000) are 3 magnitudes brighter or more
Figure 1. The luminosity versus metallicity diagram for dwarf galaxies. Crosses represent dIs. Filled symbols represent galaxies classified as BCGs or HII-galaxies: Small filled diamonds are “regular” galaxies which can be classified as Type II or iE/aE, while filled circles are galaxies that can be classified as Type I. Filled triangles are BCGs for which no classification or images were available. The three most metal-poor galaxies are labelled and shown as filled hexagons. Filled stars are luminous BCGs. Asterisks show the location of “blue amorphous galaxies” except for II Zw40 which is the filled circle falling on the short dashed line). LSBGs are shown as open squares and open pentagons Open star is H1 1225+01, the H1-cloud in Virgo. Boxes with plusses inside are quiescent (dI/LSBG) dwarfs. Candidate tidal dwarfs are shown as “T”, and dEs are shown as “dE”. The solid line shows the $M_B - O/H$ relation for dIs from Richer and McCall (1995), while the dotted line shows the same relation offset by 3.5 magnitudes, indicating the location of XBCGs. The short dashed line shows the $M_V - Z$ relation for dE/dSph from Caldwell (1998) assuming $(B-V) = 0.75$ and $[O/H] = [Fe/H]$, while the long dashed line shows the same relation assuming $[O/H] = [Fe/H] + 0.5$. Details and complete references for the object sources, their B magnitudes and metallicities are listed in KO2000.

at a given metallicity, or equivalently 0.5 dex less metal rich at a given luminosity as compared to the dI relation. The intriguing XBCGs include IZw18 and SBS 0335-052, Tololo 1924-516) (see Ostlin et al. 1999, 2001) among others.

Tidal dwarfs appear metal–rich for their metallicity because they were formed from the already enriched gas of their parent galaxies (Duc & Mirabel, 1998). Some arguments have
been given that ascribe the luminosity-metallicity correlation to the effects of selective losses of heavy elements from galaxies in supernova-driven outflows. A reduction in the effective yields (most likely due to galactic winds) can explain the observations: Garnett (2002) has shown that metal loss due to supernova-driven winds is a process at work in Ir and some spiral galaxies. Indeed, galaxies with low rotational velocities (hence low mass) loose a large fraction of metals while galaxies above this value tend to retain metals. Not only is the metallicity-luminosity relation of galaxies inferred from the SDSS providing the best evidence for galactic winds (Tremonti et al. 2004) but this relationship is expected to evolve with cosmic epoch.

At large redshifts ($z \geq 2.0$), and using emission-line ratios, Pettini et al. (2001, and references therein) already found evidence that Lyman Break Galaxies (LBGs) of undersolar abundance are 5–40 times more luminous than local systems of similar metal content, confirming that the luminosity-to-metal ratio varies with time.

7. Cosmological context

It has been possible to sketch the star-forming history of the Universe at high redshifts (Chary & Elbaz, 2001). It appears that the overall SFR of the galaxy population seems to increase from $z = 0$ to $z = 1$; this epoch is believed to be that of disc formation. The cosmic star formation rate becomes constant or slightly declining from $z = 1$ to $z = 4$ and this period is sometimes referred to as the spheroid epoch. In fact, at $z \geq 1$ more galaxies were in interactions, starbursts built on rapid time scales with high SFR/unit area hence metallicity could be high. At high redshift, the highest SFRs occur in the most dusty galaxies (sub-mm sources) telling us that a young galaxy does not necessarily mean being metal poor! Numerical simulations indicate that metal production occurs at early times (due to spheroids consecutive to the strong starburst they experience) while at $z \leq 2$ the main sites of element production become the spiral discs (Calura & Matteucci 2004). Local irregular systems have a negligible contribution to the total element production.

Numerical simulations by Cen and Ostriker (1999) predict the evolution of the metal content of the Universe as a function of density, by incorporating star formation and its feedback on the IGM. At a given gas density (corresponding e.g. to a rich cluster, a disc galaxy, dwarf etc...) their models predict an evolution with redshift, but more importantly show that metallicity is a stronger function of density than age; moreover with a considerable scatter. At low redshift, one would expect a few percent of the gas-rich dwarfs to have metallicity on the order of IZw18, without invoking their youth. This is also suggested by the Lyα absorption systems, (Shull et al. 1998). Ferrara and Tolstoy (2000) discussing the feedback from star formation in dwarf galaxies argue from this that low mass galaxies could be a major contributor to metals in the IGM.

8. Fate of metals

8.1. The mixing time scales

The fraction of metals that mixes within the ISM crucially depends on the thermodynamical status of the ISM and on the star formation history of the galaxy. The very first burst of star formation must occur in a very cold and dense medium hence radiative losses of the expanding bubbles and superbubbles become significant (i.e. comparable to the thermal energy of the cavity) in a short time-scale of the order of 10 Myr (MacLow & McCray, 1988; Recchi et al. 2001). At later times, the ISM being warmer, more diluted and irregularly structured, radiative losses will be smaller, therefore the impact of
late generation of stars into the ISM will be stronger. Freshly produced metals by these late generations of stars, will be either directly channeled along the galactic outflow or released in a warm and tenuous medium on a much larger mixing time-scales - as large as one billion year (Recchi et al. 2004; Tenorio-Tagle, 1996).

In more general terms, Roy & Kunth (1995) concede that dwarf galaxies are expected to show kpc scale abundance inhomogeneities. From an observational point of view, some galaxies support the fast mixing scenario while some do not. This is true in NGC 5253, IIZw 40 and Mrk 996 where local N/H overabundances has been attributed to localised pollution from WR stars (Kobulnicky et al. 1997; Walsh & Roy, 1993; Thuan et al. 1996). This indicates that rapid mixing can take place. However this is not true for all young starbursts even when WR stars are suspected or well observed (Oey & Shields, 2000). On the other hand IZw 18 appears to be rather homogeneous (Legrand et al. 2000) hence does not advocate in favor of the concept of rapid self-enrichment. Arguments in favor of complete mixing over long time scales lie from the observation that disconnected H II regions within the same galaxies have nearly the same abundances. Six H II regions in the SMC have log O/H = 8.13 (±0.08) while 4 in the LMC give log O/H = 8.37 (±0.25) (Russell & Dopita 1990).

The possibility that metallicities in the neutral gas phase are orders of magnitude below the H II region abundances would be an ultimate test of large scale inhomogeneities. Kunth and Sargent (1986) proposed a clean test for the self-enrichment hypothesis by using a QSO as background source to measure the abundance of metals in the neutral gas. Such a test was recently performed by Bowen et al (2005) who measured the abundance of sulfur in the neutral gas of the dwarf SBS 1543+593 to be the same as that of oxygen in one of its neighbouring HII region - at variance with self-enrichment pollution expectations. A good benchmark for the enrichment process in the early evolution of a galaxy is our Milky Way. Metal-poor halo stars (Cayrel et al. 2004) show a small spread in alpha elements. This is in agreement with the instantaneous mixing hypothesis commonly assumed in simple chemical evolution models (e.g. Francois et al. 2004). Arnone et al. (2005) confirmed the need for a fast mixing process for the alpha elements, although the large scatter in [Ba/Fe] shows that ejecta of stars in different mass ranges could have different mixing timescales.

8.2. The IGM enrichment

It is an important question to decide whether the newly produced metals leave the ISM and pollute the IGM. In principle, the energy released by stellar winds at the very early stage of a starburst (Leitherer et al. 1992) and supernovae explosions after a burst of star formation often exceeds the binding energy of dwarf galaxy, therefore the development of a galactic wind is likely...but:

**Observations:** Nearby Far-Infrared galaxies support the occurrence of galactic winds. The nearest edge-on disk galaxies show clear kinematic signatures of an outflow along the minor axis with velocities of the order of 200 to 600 km sec$^{-1}$ (Heckman, Armus & Miley, 1990). As shown by HST, FUSE and Chandra observations, clear signatures of an outflow are present in many other nearby galaxies such as NGC1705 (Heckman et al. 2001), NGC1569 (Martin et al. 2002), NGC3079 (Cecil et al. 2001), while that molecular disk-halo outflow is occurring in NGC3628 (Irwin & Sofue, 1996). Kunth and colleagues (see Mas-Hesse et al. 2003) have shown that the escape of the Ly$\alpha$ photons in star-forming galaxies strongly depends on the dynamical properties of their interstellar medium. The Lyman alpha profile in Haro 2 indicates a superwind of at least 200 km/s, carrying a mass of $\sim 10^7 M_\odot$, which can be independently traced from the H$\alpha$ component (Legrand et al. 1997). However, high speed winds do not necessary carry a lot of mass. Martin...
Daniel Kunth: *Starbursts and their contribution to metal enrichment* (1996) argues that a bubble seen in I Zw 18 will ultimately blow-out together with its hot gas component. Diffuse X-ray emissions around starburst galaxies correlating with the star formation per unit area (Strickland et al. 2004), corroborate the idea that these are the results of outflows driven by the starburst activity. The best examples of large-scale outflows driven by SNe feedback are however perhaps found at large redshifts (Pettini et al. 2001).

**Interpretations:** Even in spite of the ubiquity of outflow phenomena, there is no certainty that the outflowing gas will not recollapse towards the center of a galaxy in the future. It is possible that an outflow takes the fresh metals with it and in some cases leaves a galaxy totally cleaned of gas but the hot gas outside of the H II regions may simply stay around in the halo. The presence of outflows has been used as an indication that supernova products and the whole of the interstellar medium is easily ejected from the host dwarf systems, causing the contamination of the intra-cluster medium (Dekel & Silk 1986; De Young & Heckman 1994). This type of assumption is currently blindly used by cosmologists in their model calculations.

In a more refined approach MacLow & Ferrara (1999) models with \( \sim 10^6 M_\odot \) systems experience a complete blow-away, whereas in more massive ones only a small fraction of the gas mass escapes the galactic potential well. In these blow-out phenomena a very large fraction of metals is lost and for models with masses below or equal \( \sim 10^8 M_\odot \) almost all the metals are lost through the galactic wind. This result (that metals are ejected much more easily that pristine ISM) is pretty common (the same found Strickland & Stevens 2000 or D’Ercole & Brighenti 1999) but is at variance with Silich & Tenorio-Tagle vision (2001). They argue that the indisputable presence of metals in galaxies implies that supernova products are not completely lost in all cases: in a dwarf galaxy which has a weaker gravitational potential, these effects may result in gas loss from the galaxy unless the presence of a low HI density halo acts as a barrier. Model calculations developed by Silich & Tenorio-Tagle (1998) predict that superbubbles in amorphous dwarf galaxies must have already undergone blowout and are presently evolving into an extended low-density halo. This should inhibit the loss of the swept-up and processed matter into the IGM. Recent Chandra X-rays observations are mitigated: some young starbursts indicate metal losses from disks (see Martin, Kobulnicky & Heckman 2002) but not in the case of NGC 4449 with an extended HI halo of around 40 kpc (Summers et al. 2003).

Legrand et al. (2001) have compared Mac Low & Ferrara (1999) and Silich & Tenorio-Tagle (2001) theoretical estimates with some well-studied starburst galaxies. Values of the derived mechanical energy injection rate were compared with their hydrodynamical models predictions. The net result is that all galaxies lie above the lower limit first derived by Mac Low & Ferrara (1999) for the ejection of metals out of flattened disk-like ISM density distributions energized while most are below the limit for the low density halo picture.

### 8.3. Which galaxies enrich?

Which galaxies experience galactic winds and contribute to the chemical enrichment of the IGM? Gibson & Matteucci (1997) showed that dwarf galaxies can provide at most 15% of the ICM (intra cluster medium), giant ellipticals being responsible for 20% of it and the remaining 65% being primordial. It has been proposed that only certain elements are lost (or in different proportions) hence reducing the effective net yield of those metals as compared to a simple chemical evolution model (Edmunds, 1990). The SNe involved in such a wind are likely to be of type II because type Ia SNe explode in isolation and will less likely trigger chimneys from which metals can be ejected out of the plane of a galaxy. In this framework O and part of Fe are lost while He and N (largely
produced by intermediate stars) are not. This would result in a cosmic dispersion in element ratios such as N/O between galaxies that have experienced mass loss and those that have not. In general, as we discussed above, the flatter a galaxy is, the easier is the development of a galactic wind (Strickland & Stevens, 2000), therefore for elliptical galaxies the development of a galactic wind occurs only when the total thermal energy overcomes the binding energy of the galaxy, condition not required in flattened systems. However, the initial star formation rate in elliptical galaxy should be large enough to fulfill the condition for the onset of a galactic wind. Therefore IGM pollution due to galactic winds from giant ellipticals is likely.

Dwarf spheroidal galaxies with a more shallower potential well should favor the development of a galactic wind and their lack of gas might be explained by this phenomenon. But this is not as easy at it looks, Marcolini, D’Ercole & Brighenti (2006) simulating a spherically symmetric galaxy such as Draco failed in producing a galactic wind hence the problem is difficult to solve from the hydrodynamics and I invite the reader to look at the paper of Skillman & Bender (1995) for a thorough discussion of these problems.

A very last point concerning iron was brought to my attention by S. Recchi. A very large amount of iron is in the ICM, perhaps exceeding the amount of alpha elements (e.g. M87; Gastaldello & Molendi 2002). Since galactic winds should be enriched in alpha elements as they are released by more numerous SNeII there should be an overabundance of alpha-elements, at odds with observations. However, elements produced by SNeIa are easily channeled along the wind (the hole in the ISM is already there, releasing the efforts to leave the parent galaxy), therefore simulations of starburst galaxies give larger ejection efficiencies for iron-peak elements. Models with continuous star formation have similar ejection efficiencies of alpha- and iron-peak elements.

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