HI metal enrichment from massive star–forming regions: sudden or delayed?

Kunth Daniel

Institut d’Astrophysique de Paris, 98 bis Bld. Arago, F-75014, Paris; France

Abstract.

It now becomes possible to perform multiphase studies of the ISM from hot to molecular phases. HI and H II in star–forming gas-rich galaxies seem to exhibit differences in their metal composition in the sense that HI is less enriched in nitrogen, argon and possibly oxygen than the H II ionized gas. This observational evidence needs to be confirmed on larger sample and yet remains difficult to interpret. We review some possible interpretations. If, on the other hand, metals remain for a long time in hot gas they might ultimately cool down and mix with the original interstellar medium rather than being expelled into the intergalactic medium.

1. The quest for extreme metal poor galaxies

The epoch of galaxy formation is still an uncertain issue. The possibility that at our present epoch some uncondensed clouds of primordial matter may condense and form massive stars for nearly the first time remains unconvincing. No evidence for local unprocessed primordial cloud of gas has yet been given and the discovery of such pristine gas would be of great importance for cosmology. Good places to search for are the blue compact galaxies (hereafter BCGs, also named extragalactic H II regions) which are very deficient in heavy elements as compared to our Galaxy (Kunth & Östlin 2000). Most BCGs are rich in neutral gas which might be totally or partially unprocessed in some cases. The true metallicity of these unevolved systems could be even lower than that measured from their H II regions if they are self–enriched in heavy elements by massive stars formed in the present burst. Such a self enrichment mechanism would explain the failure to find extreme metal poor star–forming galaxies from extensive emission-line galaxies surveys (Kunth & Sargent 1986; hereafter KS86). Pantelaki & Clayton (1987) dismissed this possibility from the fact that most of the ejecta should remain for a long time in the hot gas generated by supernovæ (SN) events. In more general terms, Roy & Kunth (1995) discuss mixing processes in the interstellar medium (ISM) of gas rich galaxies and conclude that dwarf galaxies are expected to show kpc scale abundance inhomogeneities. On the other hand, chemodynamical models (Hensler & Rieschick 1998), predict that the ISM will be well mixed and chemically homogeneous through cloud evaporation.
2. Evidences for/against abundances homogeneities

Do we measure abundance inhomogeneities?

The observational situation is still not completely clear. Few dwarfs have been subject to high quality studies of their chemical homogeneity. Most dwarf irregulars seem rather homogeneous (Kobulnicky 1998) with the exception of NGC 5253 where local N/H overabundances has been attributed to localised pollution from WR stars (Kobulnicky et al. 1997). There is also marginal evidence for a weak abundance gradient in the LMC (on the scale of several kpc, Kobulnicky 1998).

The situation is less clear in BCGs: In IIIZw 40, Walsh & Roy (1993) found a factor two variation in the oxygen abundance while Thuan et al. (1996) report N/H local overabundances that they attribute to stellar WR winds. 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 II Zw 18 appears to be rather homogeneous (e.g. Skillman & Kennicutt 1993, Vilchez & Iglesias-Páramo 1998, Legrand et al. 2000) hence does not advocate in favor of the concept of self-enrichment (KS86). On the other hand recent spectroscopy of SBS0335-052 (Izotov et al. 1999) reveals small but significant variations in accordance (though to a much lesser extent) with previous results (Melnick et al. 1992).

Arguments in favor of complete mixing lie from the observation that disconnected H\textsc{ii} regions within the same galaxies have nearly the same abundances. Six H\textsc{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). Even though Dennerl et al. (2001) measure oversolar O, Ne, Mg, and Si (all type II supernovæ products) abundances in the LMC, it is not known which fraction of the processed gas is contained in hot phase and when this gas will condense into the H\textsc{i} phase. The possibility that metallicities in the neutral gas phase are orders of magnitude below the H\textsc{ii} region abundances would be an ultimate test of large scale inhomogeneities.

2.1. A galaxy with extreme properties: II Zw 18

Amongst blue compact galaxies, II Zw 18 has the lowest known heavy-element abundances in its H\textsc{ii} regions and is thus the best candidate for a young galaxy experiencing its first star formation. The utter lack of known galaxies with abundances smaller than II Zw 18, despite concentrated observational efforts has been a puzzle. As we stressed above, KS86 suggested that II Zw 18 could indeed be a primordial galaxy in which the observed H\textsc{ii} regions have been self-enriched in the current burst.

Its youth has been questioned by Aloisi, Tosi & Greggio (1999) using HST optical data and in the near infrared by Östlin (2000) who discovered a well-defined population of asymptotic giant branch stars. However Hunt, Thuan & Izotov (2003) argue that only 22% of the total mass could be contributed by older stars which in itself makes this object peculiar per se. It also contains a relatively large amount of neutral gas (Viallefond et al. 1987) and the main H\textsc{ii} region of II Zw 18 is associated with a very massive neutral cloud. The content of this large surrounding envelope has been the subject of debates. For instance
it had been suggested that this envelope may contain a significant reservoir of molecular hydrogen to account for dark matter (Lequeux & Viallefond 1980).

In any case, as part of this cloud is located on the line of sight to the ionizing star cluster, heavy elements can be detected through their absorption lines against the continuum of the ionizing stars. Spectra were first obtained with the Goddard High Resolution Spectrograph (GHRS) on board the Hubble Space Telescope (HST) in the spectral regions around the Lyman α line of hydrogen and the resonance line of neutral oxygen O i at 1302 Å. Unfortunately this line has a very strong oscillator strength ($f_{1302} = 51.9 \times 10^{-3}$) and becomes rapidly saturated, in particular at the large column densities observed ($N_{\text{H}_i} \geq 2 \times 10^{20}$ cm$^{-2}$). Results were un conclusive and let the problem with divergent conclusions (Kunth et al. 1994, Pettini & Lipman 1995). Van Zee et al. (1998) using a new value for the H i velocity dispersion were able to obtain an H i metallicity more in the range to that in the H ii regions. Izotov, Schaerer & Charbonnel (2001) still defend the view that UV lines may originate from the H ii regions leaving open the possibility that H i is pristine.

3. Far Ultraviolet Spectroscopic measurements

We now enter a time in which it becomes possible to perform multiphase studies of the ISM. In addition to the H ii regions which have been routinely studied over years from ground-based optical facilities, hot gas studies are now at reach owing to X-rays satellites such as Chandra, while the chemical composition of H i gas and the presence of H$_2$ molecules are accessible using the HST and the FUSE. Stellar spectroscopists reach the possibility to measure the atmospheric composition of stars in local galaxies. All together the understanding of galaxy evolution driven by the evolution of its primary constituents is now a feasible goal.

Given the chemically unevolved nature of some BCGs and the lack of organized gas dynamics and/or spiral arms, it is unclear where and how these galaxies formed the molecular gas thought to be required to produce the current generation of young stars. However, the remarkable absence of diffuse H$_2$ in the most metal-poor starburst galaxy IZw 18 can well be explained by the low abundance of dust grains, its high ultraviolet flux, and the low density of the H i cloud surrounding the star-forming regions (Vidal-Madjar et al. 2000).

The launch of FUSE has provided access to the rich system of far-UV absorption lines that can be seen against the 900–1200 Å continuum light that is produced by ionizing stellar clusters in BCGs. The high spectral resolution of FUSE allows to analyse and disentangle the Galactic contribution giving a possibility to retrieve the metal content of the neutral ISM of BCGs. It is now possible to measure abundances of O, Si, Ar, Fe, P by using several lines per ions and applying a procedure allowing for their simultaneous fit.

H i column densities are calculated using the Lyman series (Fig. 1). So far thirty BCGs have been observed with FUSE. The chemical composition of four BCGs have been fully investigated: IZw 18 (Lecavelier et al. 2003 and Aloisi et al. 2003), IZw 36 (Lebouteiller et al. 2003), SBS 00335-052 (Lecavelier et al. 2002) and Markarian 59 (Thuan et al. 2002).
Oxygen is produced by massive stars and released in the ISM through type II supernovae explosions and is usually taken as a reference element to investigate the composition of the ISM in extragalactic objects. Its derivation in ionized regions is very reliable while as we explained above its derivation for H\textsc{i} gas is more complicated. \textit{FUSE} allows to observe several oxygen lines but they are either saturated, midly saturated or blended with H\textsc{i} Lyman lines hence in all cases difficult to interpret. For this reason the actual results display confortable error bars and a very contrasted situation. For I Zw 18 Lecavelier et al. find \( \log (\text{O} \text{\textsc{i}}/\text{H} \text{\textsc{i}}) = -4.7_{-0.6}^{+0.8} \) which is consistent with the O/H ratio observed in the H\textsc{ii} regions (all uncertainties are 2-\( \sigma \)) while Aloisi et al. (2003) report a significantly different value with \( \log (\text{O} \text{\textsc{i}}/\text{H} \text{\textsc{i}}) = -5.4_{-0.3}^{+0.3} \) a discrepancy with the former result that awaits for clarification (see Lecavelier et al. 2003 on this point). Thuan et al. (1997) attempted to circumvent the problem of the O\textsc{i} 1302 \text{\AA} saturation in the case of SBS0335-052 and reported an extremely metal deficiency in the H\textsc{i} gas with an O\textsc{i}/H\textsc{i} ratio \( < 3 \times 10^{-7} \). However in that same galaxy the O\textsc{i}/H\textsc{i} ratio was subsequently found to be much higher using \textit{FUSE} observations of O\textsc{i} lines at shorter wavelengths and with smaller oscillator strengths (Lecavelier et al. 2002). In fact, the hypothesis of an O\textsc{i} line at 1302 \text{\AA} unsaturated was simply erroneous. It is noteworthy that O\textsc{i}/H\textsc{i} ratios
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in SBS0035–052 and Mrk 59 are similar to that of IZw 18. This may suggest that
the metallicity of the surrounding H\textsc{i} cloud is unrelated to the metallicity of the
H\textsc{ii} regions. Coincidental or not this remains to be observationally supported
using a larger sample. In any case Mrk 59 is the only object for which the
difference between the H\textsc{i} and the H\textsc{ii} regions is significant.

A more secure issue would come from the measurement of unsaturated lines
such as the S\textsc{ii} λ1256 multiplet, unfortunately out of the FUSE spectral window.

Can we derive total abundances using other elements? It is of course necessary
to pay attention to the ionization states of each species under study. Nitrogen
(Fig. 2) is of twofold interest:

- its presence in the neutral regions is well established: the ionization po-
tential of N\textsc{i} is 14.53 eV and it can be shown that the applied correction
to account for the possible presence of ionized N in the neutral gas is only
0.05 dex (Sofia & Jenkins, 1998),

- many of the N\textsc{i} lines are unsaturated hence weakly depend on the turbulent
velocity of the gas.

Figure 2. Fit of the λ1134.98 line in IZw 36. See Fig. 1 for a de-
scription of the plot. Data are binned by a factor 2 for display purposes.
The solid line is for log (N\textsc{i}/H\textsc{i})=−6.88 and shows the best fit. The
dashed line is for log (N\textsc{i}/H\textsc{i})=−5.63 (assuming the same N/H ratio
that in the ionized gas) and does not fit well the data at 3-σ.

So far the extended neutral regions of gas rich galaxies seem to exhibit abund-
ances differences between their neutral and their ionized has. If unfortunately
oxygen gives unconclusive results the most unambiguous but puzzling evidence
for such a chemical difference comes from nitrogen and argon (Lebouteiller, this
conference and Lebouteiller et al. 2003). The interpretation remains difficult.
We can identify several effects responsible for these deficiencies:
- The presence of an unprocessed neutral gas in the line of sight could
lower all the abundances in the neutral region.
- Depletion on dust grains can account for a possible iron deficiency but is
not likely to affect neither nitrogen or argon.
- Prompt metal enrichment (self pollution) can be responsible for nitrogen
and argon overabundance in the ionized gas.

Self-enrichment by SNe could account for the excess nitrogen observed in H\textsc{ii} regions w.r.t. that of the H\textsc{i} gas. On the other hand the low abundance pattern of the interstellar medium suggests ancient star-formation activity with an age of around a Gyr or a continuous low level star formation activity over several Gyr (Legrand, 2000; Aloisi et al. 2001). Such abundances differences between the two gas phases are uneasy to explain by Tenorio-Tagle’s model (1996) in which hot gas cools and later on settles down onto the disk. At present, the overall picture remains unclear and it is possible that a larger sample will help to determine more accurately the oxygen composition of the H\textsc{i}. A way out might well be to use instead phosphorus asymmetry a tracer of oxygen abundance, easier to measure in \textit{FUSE} spectra (Lebouteiller, 2003).

4. Metals from star-forming dwarfs: retention or ejection?

As they end their lives massive stars explode as a supernovae. The energy output from a SN is over a short period, comparable to that of a whole galaxy. In a galaxy with a high local star formation rate, the collective action of supernovae may lead to a galactic superwind, which may cause loss of gas. Stellar winds can also contribute to the energetics of the ISM at the very early stage of a starburst (Leitherer et al. 1992). The relative importance of stellar winds compared to SNe increases with metallicity. A continuous wind proportional to the star formation rate has been applied in models predicting the evolution of starburst galaxies. But since different elements are produced on different timescales, 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 (Matteucci & Chiosi 1983, 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 a dwarf galaxy which has a weaker gravitational potential, these effects may result in gas loss from the galaxy unless as we argue below the presence of a low H\textsc{i} density halo acts as a barrier.

Galactic winds have been observationally investigated in dwarf galaxies (e.g. Marlowe et al. 1995; Martin 1996, 1998) and more recently with the advent of the Chandra satellite. Lequeux et al. (1995), Kunth et al. (1998) and 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 the BCG 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 (1996) argues that a bubble seen in IZw 18 (see also Petrosian et al. 1997) will ultimately blow-out together with its hot gas component. Although little is known about the interactions between the
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evolving supernova remnants, massive stellar bubbles and the ISM it is possible that an outflow takes the fresh metals with it and in some cases leaves a galaxy totally cleaned of gas. This scenario clearly contradicts the self enrichment picture - unless a fraction of hot gas rapidly cools down -. But since we see some hot gas outside of the H II regions the question remains whether this gas will leave a galaxy or simply stay around in the halo?

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 of young starbursts indicate some possible metal losses from disks (Martin, Kobulnicky & Heckman 2002) but not in the case of NGC 4449 with an extended H I halo of around 40 kpc (Summers et al. 2003). In a starburst galaxy, newly processed elements are produced within a region of \( \sim 100 \) pc size. During the supernova phase the continuous energy input rate from coeval starbursts or continuous star–forming episodes, maintains the temperature of the ejected matter above the recombination limit (\( T \sim 10^6 \) K) allowing superbubbles to reach dimensions in excess of 1 kpc.

The mechanical energy released during a starburst episode accelerates the interstellar medium gas and generates gas flows. The properties and evolution of these flows ultimately determine the fate of the newly formed metals and the manner they mix with the original interstellar medium. The presence of outflows may indicate, at first, that supernova products and even the whole of the interstellar medium may be 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. However the indisputable presence of metals in galaxies implies that supernova products are not completely lost in all cases (Silich & Tenorio-Tagle 2001). Legrand et al (2001) have compared Silich & Tenorio-Tagle (2001) theoretical estimates with some well–studied starburst galaxies. They have worked out three different possible star formation history scenarios that assume either a very young coeval starburst or extended phases of star formation of 40 Myr or 14 Gyr and inferred the expected energy input rate for each galaxy using the H\( \alpha \) luminosity and/or the observed metallicity. Values of the derived mechanical energy injection rate in the three considered cases were compared with the hydrodynamical models predictions of Mac Low & Ferrara (1999) and Silich & Tenorio-Tagle (2001). Detailed calculations and accompanying figures are given in Legrand et al. (2001); we only present in Fig. 3 the resulting plot for the extended phases of star formation of 40 Myr that might be the most realistic case for starburst galaxies.

The net result (see Fig. 3) 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. Thus the mass of the extended low density halo efficiently acts as the barrier against metal ejection into the IGM.

Disk-like models clearly require less energy to eject their metals into the intergalactic medium because the amount of blown out interstellar gas that can open a channel into the intergalactic medium is much smaller than in the spheri-
Figure 3. Log of the critical mechanical luminosity (left-side axis) and Mass of the star cluster $M_{SB}$ (right-side axis), required to eject matter from galaxies as a function of $M_{ISM}$. Lower limit estimates are shown for galaxies with extreme ISM density distributions: flattened disks (lower two lines), and spherical galaxies without rotation (upper lines), for two values of the intergalactic pressure $P_{IGM}/k = 1 \text{ cm}^{-3} \text{ K}$ (solid lines) and $P_{IGM}/k = 100 \text{ cm}^{-3} \text{ K}$ (dashed lines). Plot refers to Fig1-b in Legrand et al. (2001).

cally symmetric limit, where all of the metal-enriched ISM has to be accelerated to reach the galaxy boundary. Predicted haloes, despite acting as a barrier to the loss of the new metals, have rather low densities ($< n_{halo} > \sim 10^{-3} \text{ cm}^{-3}$) and thus have a long recombination time ($t_{rec} = 1/(\alpha n_{halo})$; where $\alpha$ is the recombination coefficient) that can easily exceed the lifetime of the $\text{H} \, \text{II}$ region ($t_{HII} = 10^{7} \text{ yr}$) developed by the starburst. In such a case, these haloes may remain undetected at radio and optical frequencies until large volumes are collected into the expanding supershells.

5. Conclusions

• On average $\text{H} \, \text{II}$ gas across a given galaxy has a fairly uniform composition. Some local inhomogeneities might be due to local stellar enrichment although this picture is unsettled yet.

• Several heavy elements are found to be less abundant in the surrounding $\text{H} \, \text{I}$ gas of starburst galaxies than that measured from their $\text{H} \, \text{II}$ regions. This observational evidence is rather well established for nitrogen and argon. Oxygen turns out to be difficult to quantify but using $\text{P} \, \text{II}$ lines and P/O one is led to conclude that oxygen in $\text{H} \, \text{I}$ might also be less abundant than in the $\text{H} \, \text{II}$ region.
The above chemical differences observed between HI and H\textsubscript{II} gas phases, if real are uneasy to interpret. They may be due to the presence of unprocessed amount of gas in the line of sight, to self enrichment effects within the H\textsubscript{II} regions or else. A further statistical study involving larger sample of BCGs and Giant H\textsubscript{II} regions is under way (Lebouteiller’s thesis).

The presence of metals in BCGs that are gas-rich and star-bursting objects points towards the presence of extended HI haloes.

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