Supernovae and the IGM

James Binney

*Oxford University, Theoretical Physics, Keble Road, Oxford, OX1 3NP, U.K.*

**Abstract.** An energetic argument implies that a galaxy like the Milky Way is blowing a powerful wind that carries away most of the heavy elements currently synthesized and has impacted the IGM out to at least 180 kpc. Rich clusters of galaxies appear to be closed systems in which most heavy elements are ejected from galaxies. More supernovae are required than the yield of core-collapse SNe from a Salpeter IMF. X-ray observations imply that the IGM in groups and clusters as been strongly preheated. SNe probably cannot supply the required energy, which must come from AGN.

1. **Introduction**

Observations of both cool and hot intergalactic gas make it clear that heavy elements are by no means confined to galaxies.

Larson (1974) predicted that late in the galaxy formation process, galactic winds would carry heavy elements out into intergalactic space. Soon afterwards X-ray spectra of intracluster gas confirmed that the gas was quite metal-rich. In recent years observations of absorption lines in QSO spectra have elucidated the impact of supernovae on the diffuser gas that is found in the field, at least at high redshift. These observations imply that, from a redshift \( z > 3 \) onwards, there does not seem to be a parcel of gas that has not felt the impact of supernovae, probably mediated by galactic winds.

While the ubiquity of the products of supernovae is beyond doubt, many aspects of the interaction of supernovae and intergalactic gas are highly uncertain. Outstanding questions include: (i) in what types of galaxy were intergalactic metals manufactured? (ii) which type of supernova (core-collapse or Ia) has been most important, and at what epoch? (iii) how important have supernovae been for the entropy budget of intergalactic gas?

2. **Winds from spiral galaxies**

Most of the luminosity in the Universe comes from spiral galaxies like the Milky Way. Do such galaxies blow SN-driven winds?

Studies of the local ISM show that a significant fraction of the pressure in the ISM comes from cosmic-rays and the magnetic field. Supernovae and fast stellar winds are the main energy sources of the ISM, so the dynamical importance of cosmic rays and magnetic fields suggests that a significant fraction of the kinetic
energy which these objects pump into the ISM is channelled into cosmic rays and magnetic fields. Hence, assuming there to be \( \sim 3 \) supernova per century, the cosmic-ray reservoir is being energized at a rate \( 10^{44}/3 \times 10^9 \simeq 3 \times 10^{34} \) W. How does this power, which could build up the observed interstellar pressure within a disk 8 kpc in radius and 200 pc thick within \( \sim 10^5 \) y, manifest itself?

The local cosmic-ray energy spectrum is such that the energy is overwhelmingly contained in only mildly relativistic particles. Such particles have enormous lifetimes because they are too fast to suffer much Coulomb scattering and too slow to produce significant synchrotron radiation – which explains why the non-thermal radio luminosity of galaxies like the Milky Way is \( \sim 10^{30} \) W (Condon 1992). Hence, the energy imparted by supernovae cannot be radiated either directly or by transfer to thermal particles, and is not simply building up within the disk. So it must drive expansion of the cosmic-ray plasma: the Milky Way must be blowing a wind that is working on the local IGM at a rate \( \sim 3 \times 10^{34} \) W.

What volume within the Local Group would this wind have filled to the present epoch? There are two ways of answering this question. If the wind were expanding into a vacuum, it would expand at \( \sim 200 \) km s\(^{-1}\) and extend to \( \sim 3 \) Mpc in a Hubble time. This gives us an upper limit on the radius of influence of an \( L_* \) galaxy. A lower limit comes from assuming that the extragalactic baryons that are required by primordial nucleosynthesis theory were once distributed in galactic halos like dark matter, and the SN-driven wind raised its temperature by order the virial temperature. We assume that \( \Omega_b \simeq 0.02 \) and \( \Omega_{DM} \simeq 0.3 \), so with baryons following dark matter in a singular-isothermal halo of circular speed \( v_c \), the baryonic mass interior to radius \( r \) is given by \( M_b(r) = (\Omega_b/\Omega_{DM})(v_c^2/G)r \).

Equating the energy required to heat this material by the virial temperature to the time-integral of the SN-power, we find:

\[
 r_{\min} \sim \frac{\Omega_{DM} G E_{SN}}{\Omega_b v_c^4} \simeq 180 \text{ kpc}.
\]

We see that even the present supernova rate within the Milky Way would impact the IGM out to near the mid point to M31, and in reality the SN rate has almost certainly been substantially larger in the past.

Recently, Tripp, Savage & Jenkins (2000) have suggested that \( O^{5+} \) absorption in quasar spectra points to a major reservoir of baryons in warm \((10^5 - 10^6 \) K\) gas in galaxy groups. As Pen (1999) points out, the thermal energy of this gas cannot derive from gravity alone: without non-gravitational heating it would be so clumpy that its soft X-ray emission would violate the constraint imposed by the unresolved component of the X-ray background. It is tempting to conclude that galactic winds provide the required heat source (see below).

### 3. Supernovae in galaxy clusters

The most compelling evidence for the impact of supernovae comes from rich clusters of galaxies. Arnaud et al (1992) show that for these objects gas mass
and $V$-band luminosity are highly correlated – $M_{\text{gas}} \sim L_V^{1.9 \pm 0.3}$. At least in part the steepness of this correlation will arise for two reasons. First, more luminous clusters tend to have higher fractions of early-type galaxies, which have lower $L_V$ per unit stellar mass, $M_*$. Second, lower-luminosity clusters are less likely to attract infall, and more likely to suffer outflow of gas – Renzini (1997) finds that systems with temperature in excess of $\sim 3$ keV do not lose gas. Arnaud et al. note that $M_{\text{gas}}$ is as tightly correlated with the luminosity from E and S0 galaxies as with total luminosity: $M_{\text{gas}} \sim L_V^{1.5 \pm 0.25}$ and argue that the exponent in this relation can be taken to be unity, so that with $M/L_V$ for early type galaxies set to $\Upsilon_{E+S0} = 7 M_\odot/L_\odot$,

$$\text{constant} \sim \frac{M_{\text{gas}}}{M_*} \sim 5.1 \pm 0.7. \quad (2)$$

From the fact that $M_{\text{gas}}/M_* > 1$ it is clear that much of the IGM has never been in a galaxy.

While the bulk of the gas may be primordial, the heavy elements in it are most certainly not. With $\Upsilon_{E+S0} = 7 M_\odot/L_\odot$ the estimate of Arnaud et al. (1992) becomes

$$\frac{M_{\text{Fe}}}{M_*} \sim (2.9 \pm 0.6) \times 10^{-3}, \quad (3)$$

while Renzini (1997) finds that for clusters hotter than $\sim 2$ keV $M_{\text{Fe}}/L_B \simeq (0.02 \pm 0.01) M_\odot/L_\odot$ independent of cluster temperature. Again adopting $\Upsilon_{E+S0} = 7 M_\odot/L_\odot$, Renzini’s value of the Fe abundance becomes

$$\frac{M_{\text{Fe}}}{M_*} \sim (2.5 \pm 1.5) \times 10^{-3}. \quad (4)$$

The IGM-abundances of several $\alpha$-elements, O, Ne, Mg, and especially Si, have been determined for many clusters (Mushotzky et al. 1996). When meteoric rather than solar-photospheric abundances are used as a point of reference, the IGM proves to be only mildly $\alpha$-enhanced – by a factor $\sim 1.5$ relative to solar (Brighenti & Mathews, 1999).

What does nucleosynthesis theory have to say about these mass fractions? The picture is confused by uncertainties in the yields of Fe and to a certain extent Si, from core-collapse SNe, and the rates (current and past) of type Ia SNe.

A key input into nucleosynthetic theory is the initial mass function (IMF). I shall assume that for $M > M_\odot$ this is of Salpeter’s form, since there is now significant evidence that the IMF is universal (which is surprising) and lies near Salpeter’s form at larger masses. In particular, recent work based on Hipparcos parallaxes (Binney, Dehnen & Bertelli, 2000) does not support the contention of Scalo (1986) that the local IMF is steeper than Salpeter at $M > M_\odot$, while Kennicutt, Tamblyn & Congdon (1994) argue that measurements of H$\alpha$ fluxes from external disks rule out a steep IMF.

For a Salpeter IMF extending between 100 and 0.08 $M_\odot$ we expect 0.0068 core-collapse SNe per $M_\odot$ of star formation, and $\sim 1/3$ of the initial stellar mass would by now have been returned to the ISM. The average core-collapse SN is expected to inject $(0.1 - 0.14) M_\odot$ of Si and $(0.07 - 0.14) M_\odot$ of Fe into the ISM.
(Gibson, Loewenstein & Mushotzky, 1997), so from core-collapse SNe we expect
\[ \sim 7.8 \times 10^{-4} M_{\odot} = 1.1 \times 10^{-3} M_\odot \]
of Si and
\[ \sim 7.1 \times 10^{-4} M_{\odot} = 1.0 \times 10^{-3} M_\odot \]
of Fe, where \( M_{\odot} \approx M_\odot / 0.7 \) is the mass in stars before the onset of mass loss.

These masses fall short of those observed [eqs (3 and 4)] by a factor of
order 2. The calculation ignores the existence of intergalactic stars (Mendez et al., 1996), but it also ignores the retention of heavy elements within galaxies. In practice these two omissions will roughly cancel, and a more elaborate calculation would leave us significantly short of heavy elements.

The resolution of this shortfall is controversial. Some argue for a flatter than Salpeter IMF (David, 1997; Gibson et al., 1997). Others argue that the missing heavies were produced by type Ia supernovae (Renzini et al., 1993; Ishimaru & Arimoto, 1997) – after all more than half of the Fe in the solar neighbourhood is thought to come from type Ia SNe. A type Ia SN injects 0.16 M_⊙ of Si and 0.74 M_⊙ of Fe into the ISM (Thielemann, Nomoto & Hashimoto, 1993), so these objects inject four times as much Fe as Si, whereas core-collapse SNe inject at least as much Si as Fe. Consequently, the observed ratio of Si to Fe masses in the IGM (\~{} 0.8) constrains the importance of type Ia SNe. The big problem with imposing this constraint at the present time is uncertainty in the ratio of mean yields of Si and Fe from core-collapse supernovae: if, as, is perfectly plausible, core-collapse supernovae produce significantly less Fe than Si, one will need a good number of type Ia SNe to bring the overall ratio \( M(\text{Si})/M(\text{Fe}) \) down to \~{} 0.8 as observed.

The current rate of type Ia SNe can in principle be determined in two ways: (i) direct observation (with still depressingly uncertain results), and (ii) from models of isolated elliptical galaxies, which require the heating rate to decline towards the current epoch in such a way that galaxies of appropriate luminosity and ambient IGM pressure are now suffering cooling catastrophes in increasing numbers (Loewenstein & Mathews, 1987; Ciotti et al., 1991; Binney & Tabor, 1995). The rates in times past, which will surely differ from the present one, are well-nigh impossible to determine or predict.

4. SNe and the entropy of the IGM

If rich clusters were fashioned by gravity alone, they should evolve self-similarly. Kaiser (1991) pointed out that it is then almost inevitable that there should be more X-ray luminous clusters in the past than now. This conclusion follows because the luminosity of an individual cluster scales as the product \( M \rho \) of mass times density, and with \( n \) the usual spectral index of the primordial fluctuations,
\[ M \sim (1 + z)^{-6/(n+3)} = (1 + z)^{-3} \text{ for } n = -1, \text{ while } \rho \sim (1 + z)^3, \]
so the characteristic luminosity will be roughly independent of \( z \). The number density of freshly collapsed objects will, on the other hand, be much higher at high \( z \). Hence there should have been many more luminous clusters in the past, in contradiction with observation.

The obvious way of suppressing the X-ray luminosities of early clusters is to have them form from preheated gas, which will either not be trapped by early potential wells, or will be trapped at lower density than in the unheated case. Kaiser estimates the entropy boost required by observing that the gas density at the core of a rich cluster is about \( 10^3 \) times the current mean density, or the
mean density at $z = 9$. So we could get the gas onto the required adiabat by heating it to current cluster temperatures $\sim 10^{7.5}$ K at $z = 9$. Alternatively, we could heat it to $\left(\frac{(1 + z)}{10}\right)^2 10^{7.5}$ K at redshift $z \gtrsim 3$.

Pen’s lower limit on the entropy of gas in groups that was discussed above implies a similar energy budget. The current maximum density of the gas is only an order-of-magnitude greater than the current cosmic mean density, so two order of magnitude smaller than the maximum density of cluster gas, and the temperature would be at $\sim 10^{6.5}$ K an order-of magnitude lower than the temperature of cluster gas. So the gas would be on a slightly higher adiabat. On the other hand, it could be put onto that adiabat rather later and therefore at a smaller cost in energy.

Do SNe provide the requisite energy? The energy release per cosmic baryon is

$$\frac{E_{SN} M_{Fe}}{n_B M_{gas} y_{Fe}},$$

where $n_B$ is the number of baryons per unit mass, $E_{SN}$ is the energy and $y_{Fe}$ is the mass of iron produced by a single SN. Since core-collapse SNe produce the least Fe per unit energy, we will maximize the energy release per Fe nucleus synthesized if we assume that type Ia SNe are unimportant. Using equations (2) and (4) to evaluate equation (3) under this assumption, and then equating the result to the thermal energy per baryon, $\frac{3}{2} kT/\mu$, of a plasma of molecular weight $\mu \sim 0.6$, we find the plasma temperature to be

$$T = \frac{2\mu}{3k} \frac{E_{SN} M_{Fe}}{n_B y_{Fe} M_{gas}} \sim 1.1 \times 10^7 \text{ K.}$$

This is clearly an upper limit on the achievable temperature because it is assumes core-collapse SNe to be dominant while ignoring radiative losses, which are liable to be significant for many core-collapse SNe, because they tend to go off in dense gas clouds. My judgment is that the energy budget is too tight, even if we assume that the gas is heated as late as $z = 2$, but others may disagree. AGN are strong candidates for providing the energy if SNe cannot do the job (Begelman, this volume).

5. Discussion

As one moves down the mass scale through virial temperatures below 2 keV, the ratio of gas mass to stellar mass declines (Renzini, 1997).

One interpretation of this result is (Binney, 1980; Whitmore, Gilmore & Jones, 1993) that intrachuster gas is the material from which disks are formed in the field, and that its early enrichment to $\sim 0.3 Z_\odot$ by early-type galaxies is the counterpart of the pre-enrichment of the Galactic disk by the bulge, which Ostriker & Thuan (1975) argued is the correct solution of the G-dwarf problem. Whereas in rich clusters late-infalling, high angular-momentum gas was shocked to the virial temperature before it could form an accretion disk around a spheroid, in systems like the Local Group disks did form, and the floor metallicity, $\sim 0.3 Z_\odot$, mirrors the current metallicity of intrachuster gas. In this picture, the declining fraction of mass in the IGM as one moves to poorer and poorer
clusters simply reflects the fact that a larger and larger fraction of the original IGM has settled into disks.

The argument I have given that star-forming \( L_\star \) galaxies blow powerful winds suggests that all \( L_\star \) galaxies, cluster and field alike, lose most of their heavy elements into deep space. If this is so, conventional galaxy evolution models require substantial revision. Moreover, in this picture overwhelming quantities of metal-enriched baryons are stored in deep space. More than one tentative line of argument now suggests that this is indeed the case. Within a few years we will probably know for sure.

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