The Environmental Impact of Galaxy Evolution

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Abstract. Galaxy evolution reveals itself not only through the evolving properties of galaxies themselves but also through its impact on the surrounding environment. The intergalactic medium in particular holds a fossil record of past galaxy activity, imprinted on its thermodynamic and chemical properties. This is most easily discerned in small galaxy groups, where the gravitational heating of this gas renders it observable by X-ray telescopes while still leaving its properties highly susceptible to the effects of galactic feedback. X-ray observations of the hot gas in groups can therefore provide a view of galactic feedback history that can complement dedicated studies of AGN and star formation activity at low and high redshift. Based on high-quality X-ray data of a sample of nearby groups, we present initial results of such a study and discuss some implications for the AGN and star formation histories of the group members.

1. Galaxy Groups as Probes of Cosmic Feedback

In recent years, deep galaxy surveys such as GOODS (Giavalisco et al. 2004) have been providing a wealth of high-quality data on the properties of galaxies across a wide range of redshifts and masses. In combination with large-area surveys of the low-redshift Universe (e.g. the SDSS), this is enabling detailed studies of the history of stellar mass assembly, star formation activity, and nuclear activity across considerable look-back times, providing a much more detailed view of galaxy evolution than available just a decade ago.

However, a complete understanding of galaxy evolution and the processes driving it is unlikely to emerge from statistical considerations applied to large galaxy samples alone. One of several complimentary approaches is to consider the impact of galaxy activity on the surrounding environment. Groups of galaxies provide particularly useful laboratories for such studies, not only because they represent a very common galaxy environment in the nearby Universe, but also because they contain a hot intracluster medium (ICM) whose properties (thermal pressure, entropy, metallicity) are highly susceptible to non-gravitational processes such as those associated with galactic feedback from star formation and AGN activity. X-ray studies of this hot gas can therefore provide information on the integrated feedback activity of galaxies. Using a sample of 15 X-ray bright groups observed with Chandra, we are using measurements of the
metal distribution in groups to unravel some of the details of the history of star formation and nuclear activity in the group members.

2. Supernova Feedback and Star Formation History

From the *Chandra* data, we have measurements of the radial distribution of the abundance of iron and silicon in the intragroup gas for all 15 systems (details of the group sample and data reduction can be found in Rasmussen & Ponman 2007). For an assumed set of supernova (SN) yields (Iwamoto et al. 1999; Nomoto et al. 2006), the results for either element can be uniquely decomposed into contributions from SN Ia and SN II and the results then stacked to provide mean profiles for the entire sample. In Fig. 1 we show the resulting average contribution of SN Ia relative to that of SN II within the sample, plotted as a function of radius in units of $r_{500}$. The abundance pattern clearly implies a strong dominance of SN II enrichment at large radii, where most of the intra-group gas resides. Comparison to the ratio of SN Ia vs SN II measured in

![Figure 1](image_url)

Figure 1. The mean number ratio of SN Ia vs. SN II in our groups as inferred from the ICM enrichment pattern, with the shaded region representing the typical relative uncertainty of 25%. For comparison, dashed lines show observed and predicted ratios in different redshift intervals from deep field data (Dahlen et al. 2004).

the GOODS survey (Dahlen et al. 2004) over a range of redshifts shows that our inferred SN ratios well outside the group cores, at $r \gtrsim 0.5r_{500}$, are inconsistent with observed values at low-to-intermediate redshifts ($z \lesssim 0.6$) but broadly agrees with predictions at $z \gtrsim 1.5$. The comparison data involve measured SN Ia rates out to $z \approx 1.8$, and SN II rates beyond $z \approx 1$ as predicted from evolutionary models of the cosmic star formation rate (see Fig. 2 in Dahlen et al. 2004).

The immediate implication of Fig. 1 is that most enrichment, and hence SN and star formation activity in the groups, must have taken place reasonably close to the peak of the cosmic star formation rate at $z \sim 2 - 3$.

Further insight may be gained by considering the total metal mass in the groups generated by each of the two SN types, normalized by the aggregate $K$-band luminosity $L_K$ of the group members. Using the adopted SN yields
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and the SN rate per unit $L_K$ (Mannucci et al. 2005) observed in local early-type galaxies (which dominate the optical output in our groups), these metal mass-to-light ratios can be translated into enrichment time-scales. The latter will be lower limits, however, because we do not account for metals locked in stars or metals ejected beyond $r_{500}$ by galaxy winds, nor for the fact that $L_K$ must have been smaller in the past due to the continued growth of stellar mass in group members and the addition of further members over time. Fig. 2 (left) shows the results for iron from SN Ia, revealing time-scales in excess of $\gtrsim 10$ Gyr in many cases and suggesting that SN Ia at current rates cannot have produced the required amount of Fe in several of the groups. This issue is even more acute for SN II, for which only upper limits to their rate in local early-types are available. Even if, for the sake of argument, assuming SN II rates in line with those of nearby late-type spirals for all galaxies except the central brightest group galaxy (BGG), the time-scales are still prohibitively large in most cases (Fig. 2 right). Hence, the inferred enrichment time-scales require much higher specific SN rates in the past in the group members, independently confirming the well-established need for a rise in the cosmic star formation rate density out to at least $z \sim 2 - 3$, as inferred from galaxy surveys. While similar results have been reported for massive galaxy clusters (e.g. Finoguenov et al. 2000), this has not previously been tested at the far more common mass scale of galaxy groups.

3. Constraining SN and AGN Feedback

Assuming that energy and metals have been released proportionally from supernovae to the ICM, the SN ratios and metal masses implied by Figs. 1 and 2 allow us to estimate the total SN energy imparted to the hot gas for an assumed SN explosion energy of $10^{51}$ erg. The resulting values within $r_{500}$, shown in Fig. 3 (left), scatter around a mean of $\sim 0.6$ keV per ICM particle, with no clear trend with group “mass” $\langle T \rangle$. Both the mean and scatter are in broad agreement with
results of hydrodynamical simulations of groups involving momentum-driven galaxy winds to account for ICM enrichment (Davé et al. 2008).

In principle, the inferred SN energies can also help constrain the impact of AGN feedback in the groups. As a first crude step, one could argue that the combined energy input from these feedback processes cannot substantially have exceeded the sum of the ICM thermal energy and its integrated energy losses without unbinding the hot gas (according to the virial theorem). Under this assumption, and evaluating the total radiative energy losses from the ICM on the basis of its current X-ray luminosity integrated over a 10 Gyr timescale, the resulting total allowed AGN heating energy in each group is shown in Fig. 3 (right). This would suggest that for a typical $T \sim 1$ keV system with a total stellar mass $M_* \sim 1 \times 10^{12} M_\odot$, the integrated AGN heating energy cannot substantially have exceeded $\sim 10^{49}$ erg per $M_\odot$ of stellar mass. To some extent, however, the above approach mainly probes the resilience of the current ICM to additional heating, and it also neglects any bulk kinetic energy imparted to the gas which may have modified its density distribution. Such a contribution could be substantial, especially in the poorest systems, but should more accurately reflect the maximum energy input that can have occurred in the groups. Hence, more robust constraints on AGN feedback would arise from assessing the amount of work done against gravity in establishing current gas mass fractions and distributions within $r_{500}$ relative to those of massive clusters.

Assuming that the AGN heating energy in Fig. 3 has been released over a 10 Gyr timescale, the resulting time-averaged heating power in the groups is typically an order of magnitude larger than the current mechanical AGN luminosity of the BGG, as estimated from its observed 1.4-GHz radio power and the relation of Birzan et al. (2004). Significantly more powerful AGN activity in the past within these groups is thus allowed, but not necessarily required, by the above results, in qualitative agreement with the inferred rise in the AGN luminosity density out to $z \approx 2$ (e.g. Hopkins et al. 2007). Some further implications for AGN accretion and supermassive black hole growth can be obtained by estimating current central black hole masses $M_{\text{BH}}$ from the observed BGG bulge velocity dispersion (e.g. Gebhardt et al. 2000). The energies in Fig. 3 then provide rough upper limits to the efficiency $\eta \sim E_{\text{AGN}}/(M_{\text{BH}}c^2)$ with which mass

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Left: SN energy per ICM particle associated with the observed ICM metal masses. Right: Total allowed AGN heating energy as a function of total stellar mass in each group.}
\end{figure}
accreted by a central black hole in the BGG’s has been converted into heating energy in the groups. On average, this number is $\eta \approx 1 - 2\%$ for our sample, rising to $\eta \approx 5\%$ in the hottest groups. Although these numbers should clearly be regarded as tentative at present, it is interesting to note that they are consistent with estimates of the ratio between black hole accretion rate and AGN jet power in bright elliptical galaxies ($\approx 2\%$; Allen et al. 2006).

4. Summary

Our work demonstrates that the SN and AGN feedback history of galaxies can be probed by studying how such feedback processes have affected the hot gas surrounding galaxies in nearby galaxy groups. This provides a useful complementary approach to those based on large multi-wavelength galaxy surveys. Specifically, comparison of the observed amount of metals in the hot intragroup gas to the present-day optical properties of the group members indicate much higher supernova and star formation rates per stellar mass in the past. By further requiring that the observed metal masses be produced within a Hubble time, these findings could in principle be quantitatively checked against models predicting the redshift evolution of the specific star formation rate and stellar mass in galaxies of a given present-day mass.

Our observations also enable crude constraints on the integrated impact of AGN feedback from the group members, providing rough upper limits to the total AGN heating energy released per stellar mass, and to the efficiency with which central supermassive black holes have converted accreted mass into heating energy. With some modifications, our approach could eventually deliver robust constraints on models of galaxy formation and evolution which include the growth of central supermassive black holes and the associated AGN feedback.

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