Implications of Abundance Gradients in Intracluster Gas

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Abstract. Analysis of spatially resolved ASCA spectra of the intracluster gas in Abell 496 confirms that metal abundances increase toward the center. We also find spatial gradients in several abundance ratios, indicating that the fraction of iron from SN Ia increases toward the cluster center and that the dominant metal enrichment mechanism near the center must be different than in the outer parts.

1 Introduction

While the metals observed in intracluster gas clearly originate from stars, how the metals got from stars into the intracluster gas remains controversial. The two global metal enrichment mechanisms most commonly considered are supernovae-driven protogalactic winds from early-type galaxies\textsuperscript{11} and ram-pressure stripping of gas from cluster galaxies\textsuperscript{4}. At the centers of cD clusters, accumulated stellar mass loss from the cDs may also contribute to the observed metal distribution. In principle, the imprints of these enrichment mechanisms can be distinguished by the chemical mix and spatial distribution of heavy elements in intracluster gas. Protogalactic winds, powered by Type II supernovae from early generations of short-lived, massive stars, may distribute metals throughout clusters. Ram-pressure stripping would be most effective near cluster centers and should deposit gas from galaxy atmospheres with considerable supplemental enrichment from Type Ia supernovae, since stripping is a more secular, ongoing process; SN Ia have longer-lived progenitors (accreting white dwarfs) and different elemental yields than SN II. Accumulated stellar mass loss in central cDs should have somewhat higher abundances than gas stripped from other early-type galaxies (but similar abundance ratios) and may have a different spatial profile than stripped gas.

Unfortunately, residual uncertainty in the theoretical elemental yields from SN II have allowed different interpretations of recent ASCA spectroscopy of intracluster gas. The yield models adopted by some investigators\textsuperscript{8,10} imply that global intracluster metal abundances are consistent with SN II ejecta, supporting the protogalactic wind enrichment scenario. However, we and others, using dif-
ferent theoretical yield models for SN II, find that as much as 50% of intracluster iron comes from SN Ia\[^2\][^3][^5][^11]. Somewhat more than half of the global iron comes from SN II, which can be readily attributed to protogalactic wind enrichment. However, the presence of large quantities of iron from SN Ia throughout clusters is problematic: is ram pressure stripping so effective that it contaminates the outer parts of clusters as much as the central regions?

Since the detailed spatial distribution of elements in intracluster gas may offer clues about the dominant metal enrichment mechanism(s), we analyzed ASCA observations of Abell 496: analysis of previous Ginga and Einstein X-ray satellite data indicated that it has centrally enhanced abundances\[^15\].

### 2 Analysis of Abell 496

We jointly fitted isothermal emissivity models to spatially resolved spectra of Abell 496 from all four ASCA instruments. Tying individual elemental abundances together in these fits, we find the metal abundance increases from 0.36 solar in the outer 3 – 12' region to 0.51 solar within 3' (see Fig. 1). Allowing the abundances of individual elements to vary independently, we find that iron, nickel and sulfur abundances are centrally enhanced. Our results are the same when we include a cooling flow spectral component for the emission from the central region.

We also found significant gradients in several abundance \textit{ratios}: Si/S, Si/Ni and S/Fe. Having gradients in abundance ratios implies that the proportion of SN Ia/II ejecta is changing spatially and that the dominant metal enrichment mechanism(s) near the cluster center must be different than in the outer parts.

We compared an ensemble of observed abundance ratios to theoretical expectations of yields from SN Ia\[^12\][^14] and SN II\[^3\] in order to estimate the relative

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**Figure 1:** Elemental abundance distribution (driven by iron) in Abell 496.
Figure 2: Iron mass fraction from SN Ia in inner (0 − 2′) and outer regions (3 − 12′) of Abell 496, from an ensemble of elemental abundance ratios.

proportion of SN Ia/II ejecta in Abell 496. An ensemble of ratios is required, since there are large theoretical uncertainties in the yields of individual elements.

Fig. 2 illustrates various estimates of the iron mass fraction due to SN Ia in inner (0 − 2′; filled circles) and outer (3 − 12′; empty circles) regions of the cluster. The ensemble of the five best-determined abundance ratios collectively and individually indicate that the proportion of SN Ia ejecta increases toward the center. The average of the five individual estimates of the iron mass fraction from SN Ia is also indicated in Fig. 2: the proportion of ejecta from SN Ia is ∼ 46% in the outer parts, rising to ∼ 72% within 2′. The central increase in the proportion of SN Ia ejecta is such that the central iron abundance enhancement can be attributed entirely to SN Ia ejecta.

3 Enrichment Mechanisms

The central metal abundance enhancements in Abell 496 are not likely to be caused by ram pressure stripping of gas from cluster galaxies. The gaseous abundances measured in most early-type galaxies by ASCA\cite{7} and ROSAT\cite{1} are 0.2-0.4 solar, significantly less than the 0.5-0.6 solar abundance observed at the cluster center. Only the most luminous ellipticals, which also tend to be at the centers of galaxy clusters or groups, are observed to have gaseous abundances of 0.5-1 solar. If ram pressure stripping is effective in the cluster, it would act to dilute the central abundance enhancement. If ram pressure stripping is not the primary source of metals near the cluster center, where it should be most effective, it is an even less likely source of metals in the outer parts of the cluster.

The central abundance enhancement is also unlikely to be due to the secular
accumulation of stellar mass loss in the cD. If it were, then other giant ellipticals which have not been stripped should have comparable ratios of iron mass to optical luminosity. NGC 4636 is among the most X-ray luminous ellipticals and may be at the center of its own small group. However, NGC 4636 has a ~10-20 times smaller iron mass to light ratio in its vicinity compared to the cD of Abell 496.

We propose instead that the bulk of intracluster gas is contaminated by two phases of winds from early-type galaxies: an initial SN II-driven protogalactic wind phase, followed by a secondary, less vigorous SN Ia-driven wind phase, contaminating the bulk of intracluster gas with comparable masses of iron. The secondary SN Ia-driven winds would be ~ 10 times less energetic than the initial SN II-driven protogalactic winds, since SN Ia inject ~10 times less energy per unit iron mass than SN II and the observations indicate that comparable amounts of iron came from SN Ia and SN II. Less vigorous secondary SN Ia-driven winds would allow SN Ia-enriched material to escape most galaxies, but not clusters. However, the secondary SN Ia-driven wind from a central dominant galaxy may be smothered, due to the galaxy’s location at the bottom of the cluster’s gravitational potential and in the midst of the highest ambient intracluster gas density. Such a smothered wind could generate the metal abundance enhancement seen at the center of Abell 496, which has the chemical signature of SN Ia ejecta.

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References
[1] Davis, D. S. & White, R. E. III 1996, ApJ, 470, L35
[2] Dupke, R. A. & White, R. E. III 1999a, ApJ, in press, astro-ph/9902112
[3] Dupke, R. A. & White, R. E. III 1999b, ApJ, in press, astro-ph/9907343
[4] Gunn, J. E. & Gott, J. R. III 1972, ApJ, 176, 1
[5] Ishimaru, Y. & Arimoto, N. 1996, PASJ, 49, 1
[6] Larson, R. B. & Dinerstein, H. L. 1975, PASP, 87, 911
[7] Loewenstein, M. et al. 1994, ApJ, 436, L75
[8] Mushotzky, R. F. & Loewenstein, M. 1997, ApJ, 481, L63
[9] Matsumoto, et al 1997, ApJ, 482, 133
[10] Mushotzky, R. F. et al. 1996, ApJ, 466, 686
[11] Nagataki, S. & Sato, K. 1998, ApJ, 504, 629
[12] Nomoto, K. et al. 1997, Nuclear Physics A, Vol. A621
[13] Nomoto, K. et al. 1997, Nuclear Physics A, Vol. A616
[14] Nomoto, K., Thielemann, F.-K. & Yokoi, K. 1984, ApJ , 286, 644
[15] White, R. E. III et al. 1994, ApJ, 433, 583