Constraining the Age of Fossil Groups with Chandra

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INTRO

Fossil groups (FGs) are classically defined as systems dominated by a single giant elliptical galaxy and with a 2 magnitude difference between the first and second rank galaxies (in R-band) within 0.5 r_{200}. They are bright sources of extended X-ray emission ($L_{X,bol}$>10^{42} h_{50}^{-2} erg/s). Even though the first of these systems was discovered more than a decade ago (Ponman et al. 1994), their origin and evolution are still strongly debated. This is mostly due to the low number of fossil groups with good quality X-ray and optical data available.

FGs were originally thought to be the cannibalistic remains of galaxy groups that lost energy through dynamical friction, perhaps the final stage of compact groups (e.g. Mulchaey & Zabludoff 1999). This idea is consistent with several observational characteristics including the high X-ray luminosities (L_X), the large gap in the luminosity function at L* in the central regions and the strong correlation of total L_X to the optical luminosity of the cD. Given the expected large times involved in dynamical friction and the observed lack of X-ray substructures, this model would imply that FGs formed early and were undisturbed for a very long time (Ponman et al. 1994; Jones et al. 2000; Vikhlinin et al. 1999).

Are They Groups?

More recently, X-ray and optical measurements of FGs have shown several inconsistencies with this formation mechanism.

Firstly, the X-ray measured temperature (T_X) of the FG's intergalactic medium is similar to that of clusters, sometimes in excess of 4 keV (e.g. RX J1416.4+2315; Khosroshahi et al. 2006).

Recent measurements of galaxy velocity dispersion in FGs (Mendes de Oliveira 2006; Cypriano et al. 2006) seems to be consistent with T_X measured, at least for the few FGs with relatively good X-ray data. This is further suggested by their (not atypical) location in the L_X-T_X relation (e.g. Khosroshahi et al. 2007 – Fig1).

If this is confirmed, it would suggest that they have relatively deep gravitational potential wells, typical of clusters, not groups. The lack of bright galaxies in central regions in a "cluster-sized" potential make these systems very puzzling.

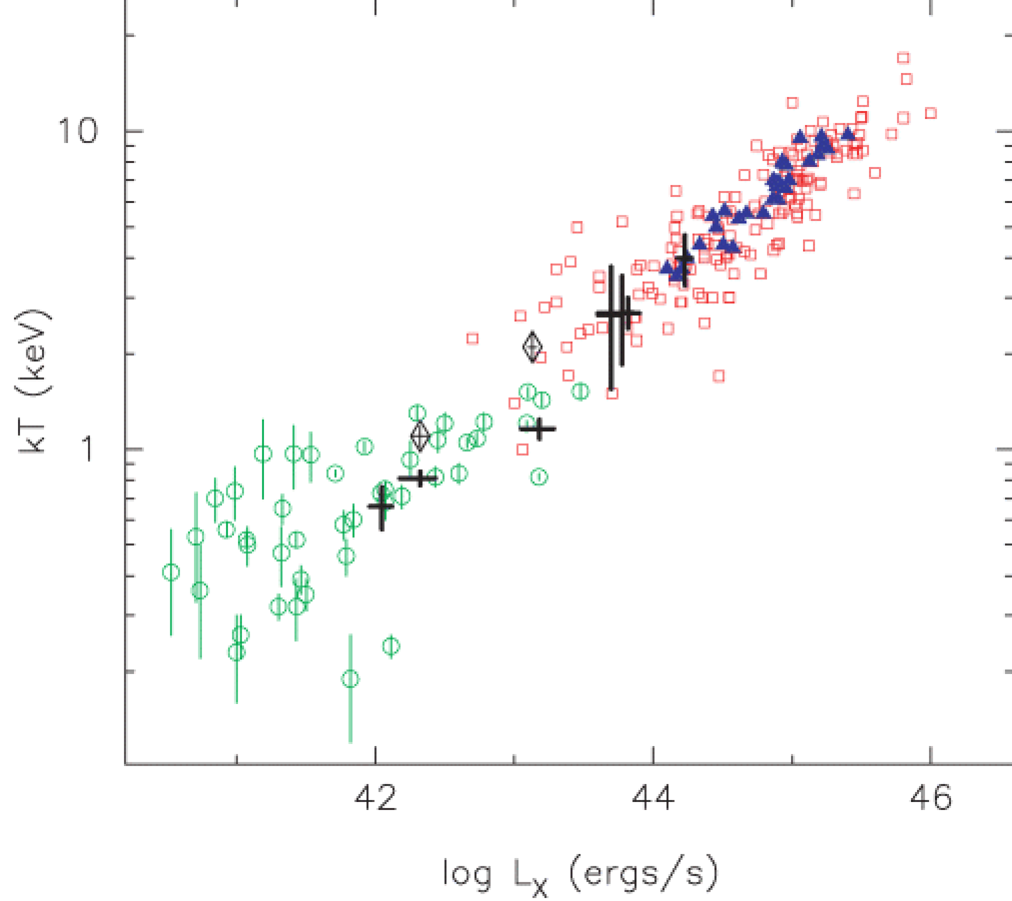


Fig.1 - L_X-T_X relation for FGs, from Khosroshahi et al. 2007 – Clusters are red+blue, groups are green and FGs are the data points.

Are They Old?

So far with the (poor) data available, the X-ray derived mass profiles (assuming hydrostatic equilibrium) correspond to very high values of the concentration parameter c_{200} (Fig 2). Given the correlation found between c_{200} and formation epoch in N-body simulations of ΛCDM cosmologies (Wechsler et al. 2002), FGs should be very old ($z_{formation}$>1.5).

Additional support for early formation of FGs comes from recent numerical+hydro simulations, which suggest a correlation between formation epoch and magnitude difference of 1st and 2nd brightest galaxies in simulated groups, the older groups having higher magnitude differences (D'onghia et al. 2005 – Fig3**)**. The latter suggest a typical FG formation age of 4.7-6.5 Gyr (0.75<z<1.3) as opposed to regular groups (~ 6.5-8.5 Gyr).

On the other hand, the cooling time of FGs is observed to be significantly below the Hubble time (e.g., RX J1416.4+2315, ESO 3060170, Sun et al. (2004); NGC 6482, Khosroshahi et al. (2004, 2006), *but they typically lack cooling cores*, indicating a more recent formation time. The fact that regular groups often show cooling cores (e.g. Finoguenov & Ponman 1999) suggests that FGs formed "after" regular groups.

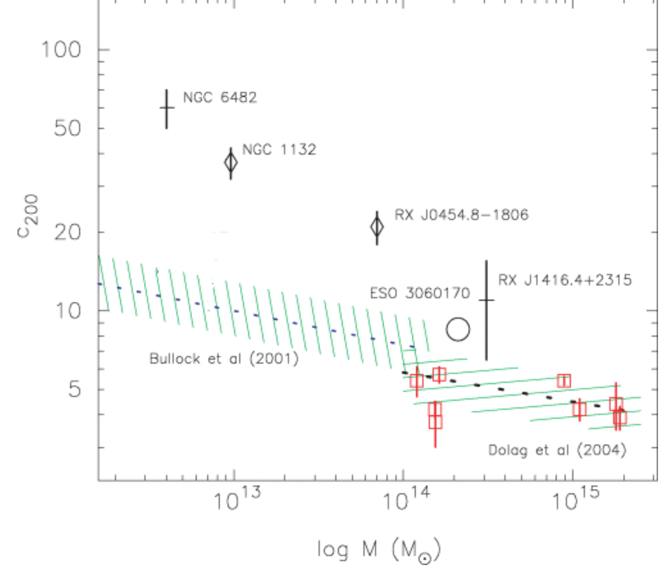


Fig 2 -M–c_{200} relation: comparison between the mass concentration in fossils and non-fossil groups and clusters. Three fossils with resolved temperature profile and two isolated OLEGs (diamonds) are compared with non-fossil clusters (open squares). The expected values from the numerical studies are also presented (dotted). From Khosroshahi, Ponman & Jones (2007).

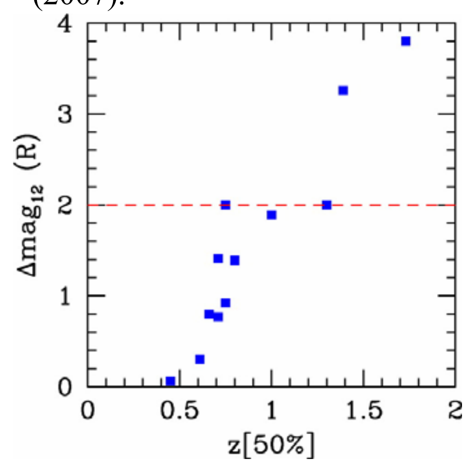


Fig3- $\Delta m_{12,R}$ of each simulated group as a function of formation time defined as the epoch in which the group assembled 50% of the system's final mass

The most popular mechanism proposed to “wipe out” the big galaxies surrounding the central dominant galaxy is still considered to be cannibalism through dynamical friction. This process per se does not impose strong constraints to the age of FGs. Even though dynamical friction needs generally a significant amount of time to work (on the order of a Hubble time), the characteristic accretion time is directly proportional to the impact parameter of the satellite galaxies (D’Onghia et al. 2005), which may have a wide range of variation (10-100 kpc corresponding to 1.2-12 Gyr), according cosmological simulations.

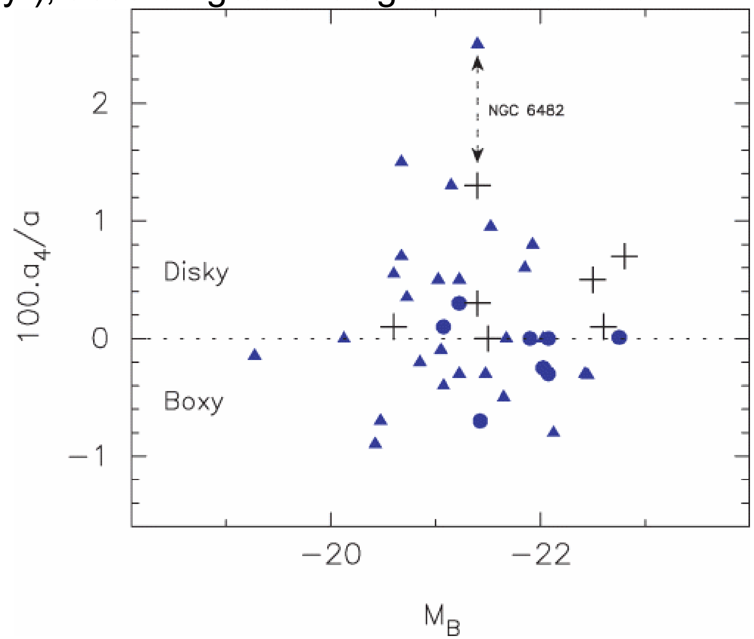


Fig4- The variation in isophotal shapes of early-type brightest group or cluster galaxies, and those in fossil groups (crosses), with the optical luminosity of the brightest galaxy. The comparison sample is a combination of early-type BGGs (triangles) and BCGs (circles) from Ellis & O'Sullivan (2006), for which a_4/a values (based on the 4th Fourier coefficient B4) were available. From Khosroshahi, Ponman & Jones (2006).

Recent optical analyses of the central galaxies of 7 FGs showed that their isophotes are disky (Fig4). This is consistent with secondary gas infall (Khochfar & Burkert 2005), which implies that group spirals took part in the merging. Galaxy merging involving early and late type galaxies, should be accompanied by star formation bursts (e.g. van Dokkum et al. 1999), driving subsequent metal rich SNII-driven galactic winds or superwinds (e.g. Strickland et al. 2004, Heckman et al. 1990). These secular winds would deposit metals and energy into the central gas. This extra energy probably contributes to explain the typical lack of a cooling core in FGs. The merger induced wind metal injection would make the central SN Ia/SN II ejecta of FGs different (lower) from that of normal groups and similar sized clusters and this can be tested through the analysis of elemental abundance ratios, as explained below.

The elemental abundance for an optically thin plasma can be directly associated to the SN Type enrichment of the gas (e.g. Mushotzky et al. 1996). Since SN Ia and II explosions produce different amounts of different elements, the SN Ia/II contamination fraction in the ICM can be determined through the X-ray measurements of individual elemental abundances (e.g. O, Si, S, Fe) and their ratios. The fraction of SN Ia/SN II pollution in the ICM shows often radial gradients (e.g. Dupke & White 2000a,b; Allen et al 2001; Finoguenov et al. 2000), the central region having a higher SN Ia/SN II ratio for cold clusters (T<6-7 keV) and groups of galaxies.

While SN II-powered protogalactic winds will tend to disperse metals into the ICM in a more instantaneous and homogeneous form, ram-pressure stripping will distribute the SN Ia polluted ejecta in a more centralized way, given that its effectiveness is proportional to the ICM gas density. This would be a slower and continuous process that should increase not just the central Fe abundance but also the central SN Ia Fe mass fraction with time (Fig5).

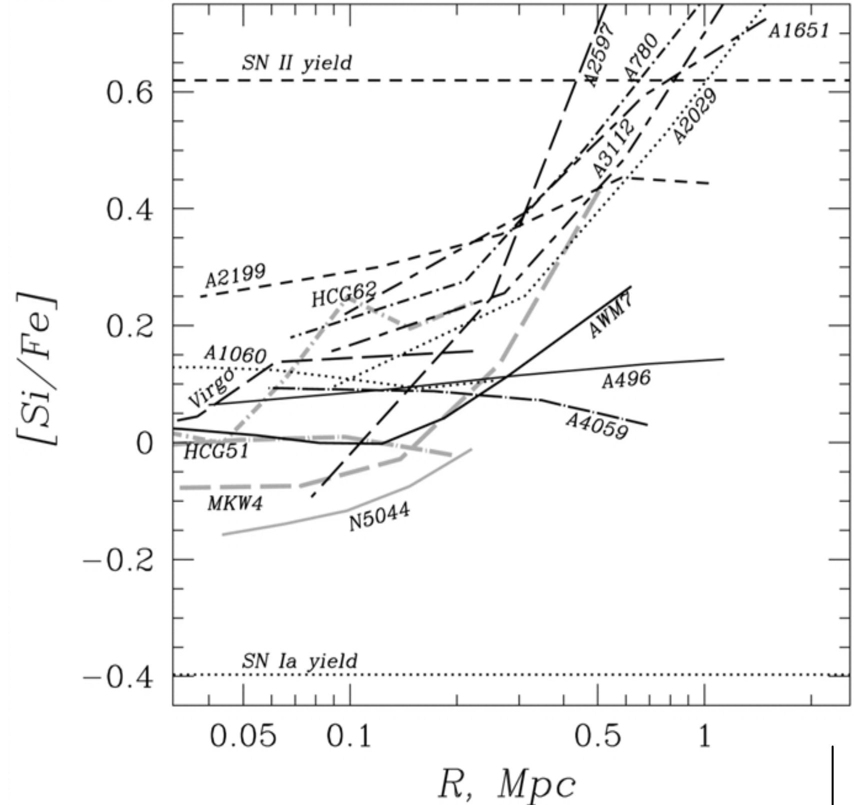
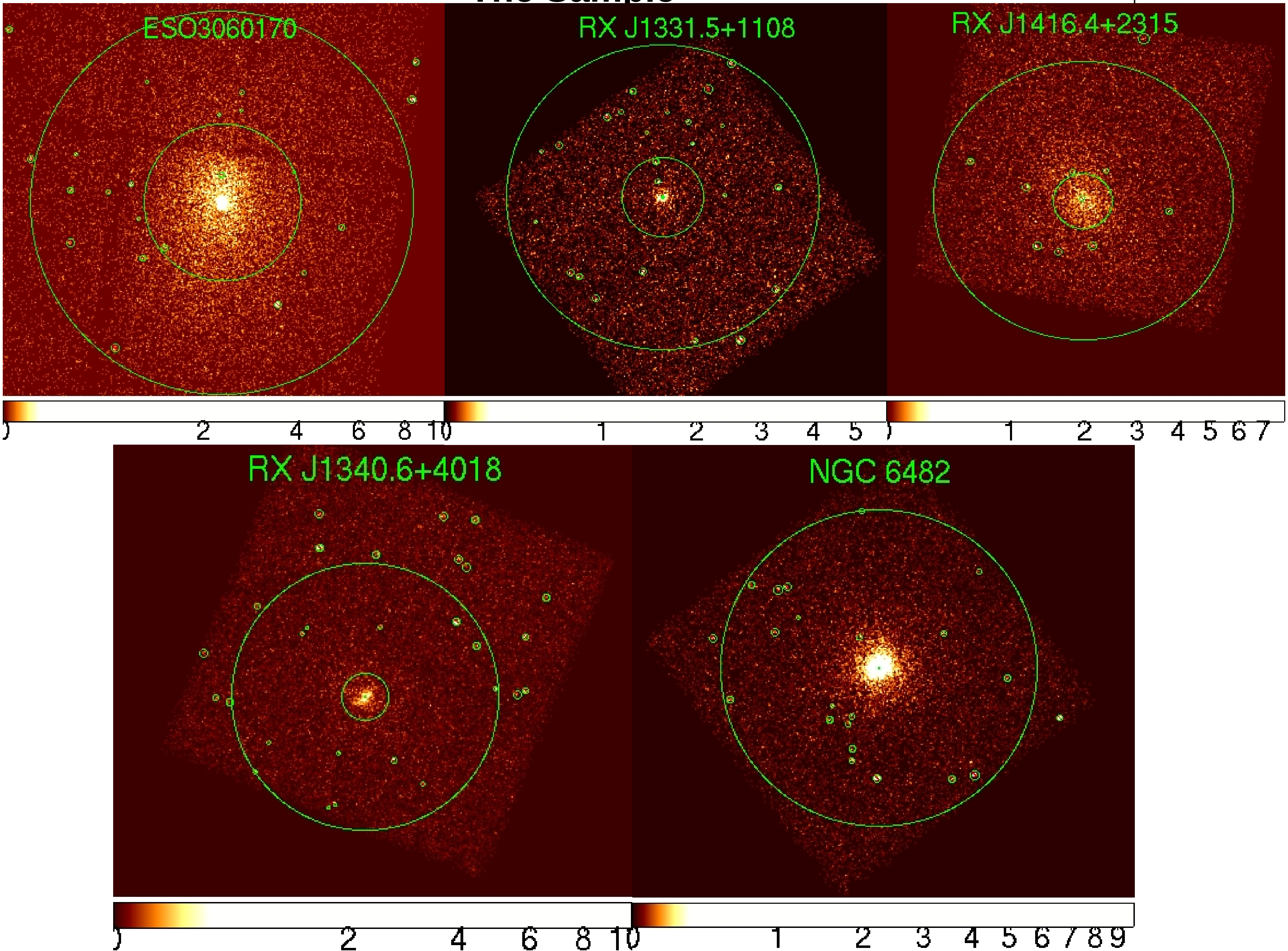


Fig5- [Si/Fe] vs. radius. Gray lines represent groups, and black lines represent clusters. From Finoguenov, David & Ponman 2000.

For an old undisturbed system the central SN Ia Fe mass fraction should be even more enhanced than that found for regular groups. *If, on the other hand, the galaxy merger(s) that wiped out the galaxies in the central regions of FGs happened at later times, secular central SN II-powered winds ejecta would tend to erase the previous central SN Ia Fe mass fraction dominance.*

The Sample


ESO3060170
RX J1331.5+1108
RX J1416.4+2315
RX J1340.6+4018
NGC 6482
0 2 4 6 8 10
0 1 2 3 4 5
0 1 2 3 4 5 6 7
0 2 4 6 8 10
0 1 2 3 4 5 6 7 8 9

DATA REDUCTION

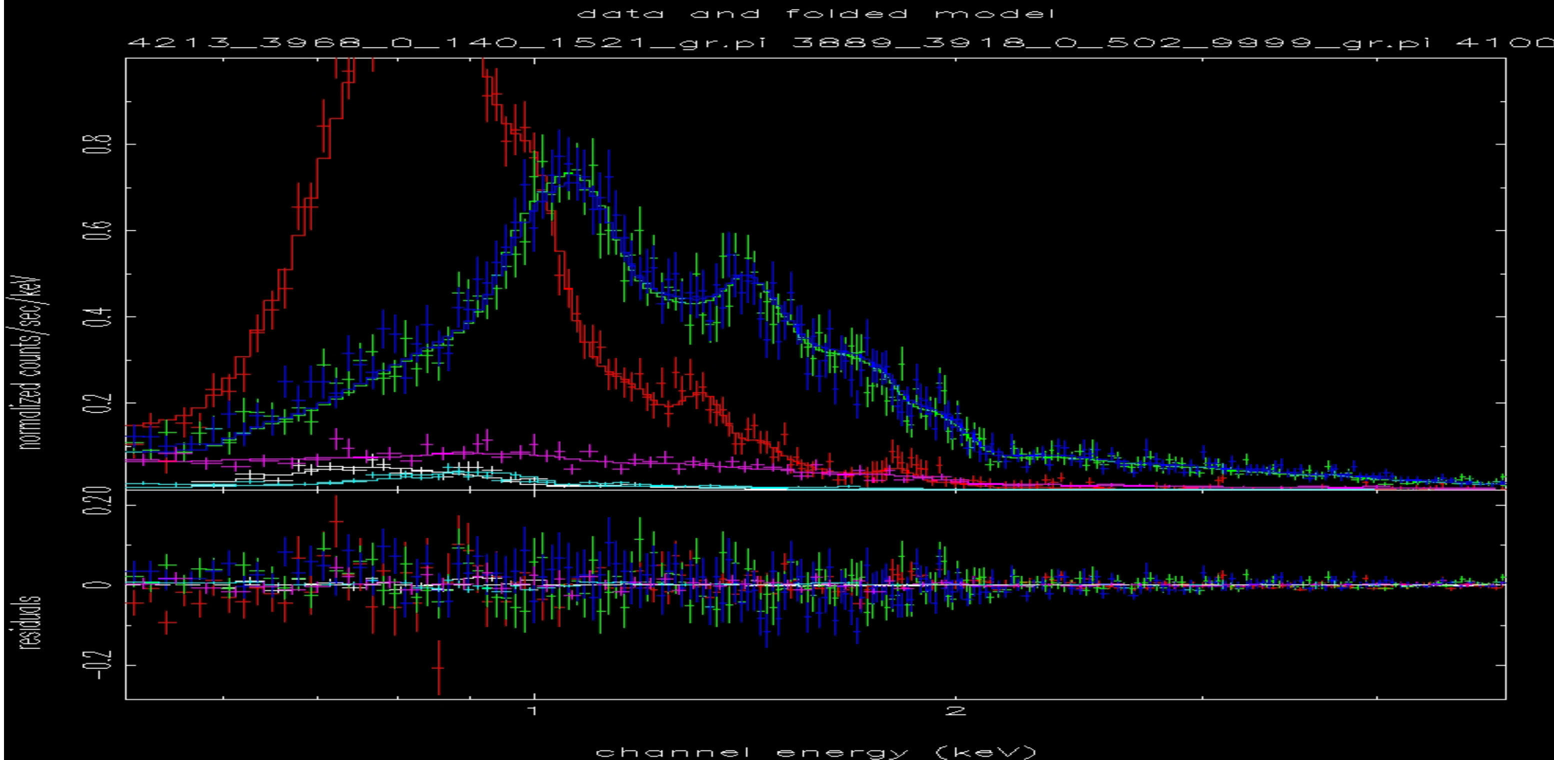
The data presented here were reduced with **Ciao** 3.2.0 with **CALDB** 3.0 using the standard procedure. Grades 0,2,3,4,6 were selected. ACIS particle background was cleaned as prescribed for VFAINT mode. A gain map correction was applied together with PHA and pixel randomization. Point sources were extracted and the background used in spectral fits was generated from blank-sky observations.

Here we show the results of spectral fittings with **XSPEC** V11.3.1 (Arnaud 1996) using the **VAPEC** thermal emission model. Metal abundances are measured relative to the solar photospheric values of Anders & Grevesse (1989). Galactic photoelectric absorption was incorporated using the **WABS** model (Morrison & McCammon 1983), with the H column density fixed at the best fit global values. Spectral channels were grouped to have at least 20 counts/channel. Energy ranges were restricted to 0.5-6.5 keV.

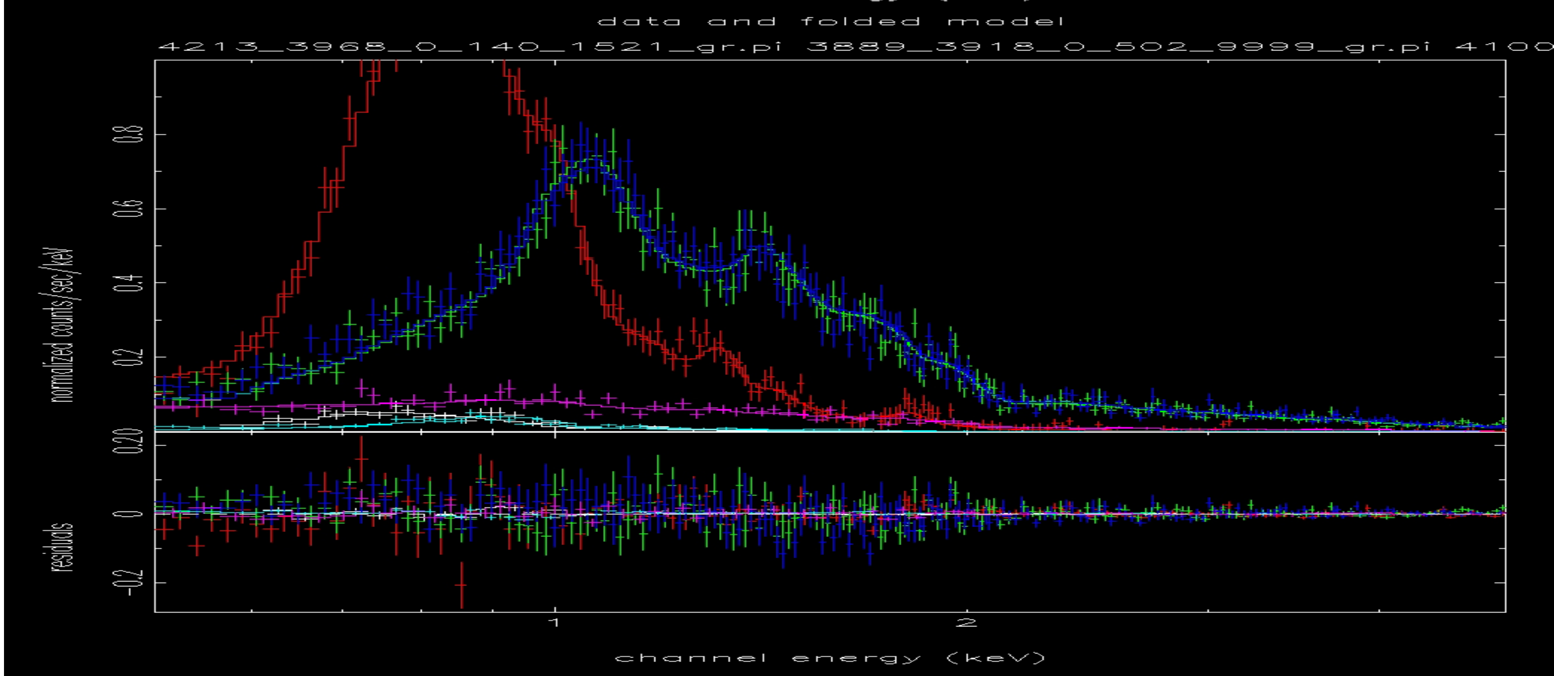
To be able to have enough statistics to perform the chemical analysis, for all FGs (RX J1416.4+2315 at z=0.138, RX J1340.5+4017 at z=0.171, ESO 3060170 at z=0.0358, RX J1331.5+1108 at z=0.0790) we selected two regions: The inner cooling radius, assumed to be 100 h_{75}^{-1} kpc and an outer region. For NGC 6482 at z=0.013, we can only define the inner region.

The correspondence between abundance ratios and SN Ia/II Fe Mass Fraction was done using the yields of Nomoto et al. 1997.

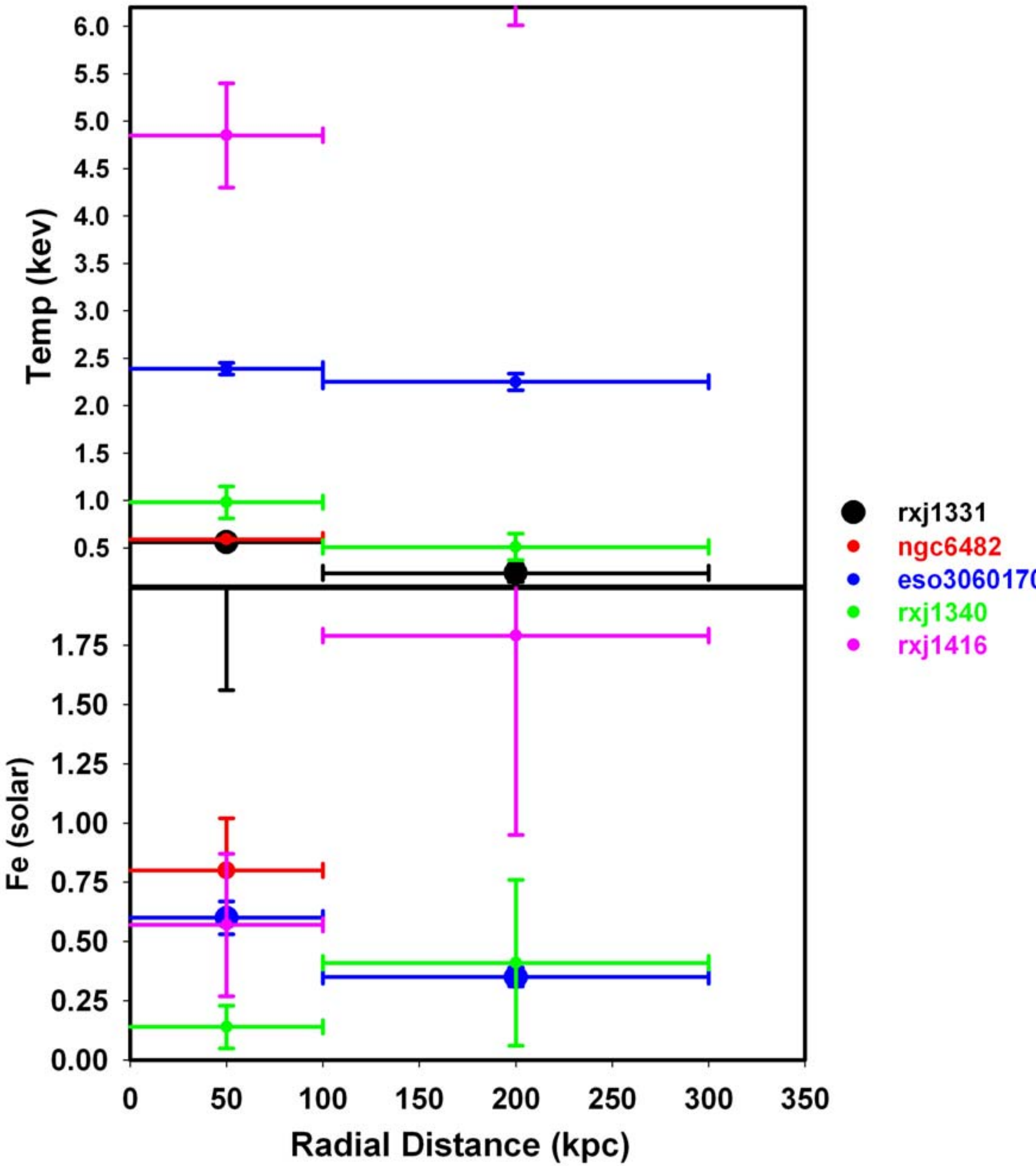
Inner region
All FGs



Outer region
All FGs



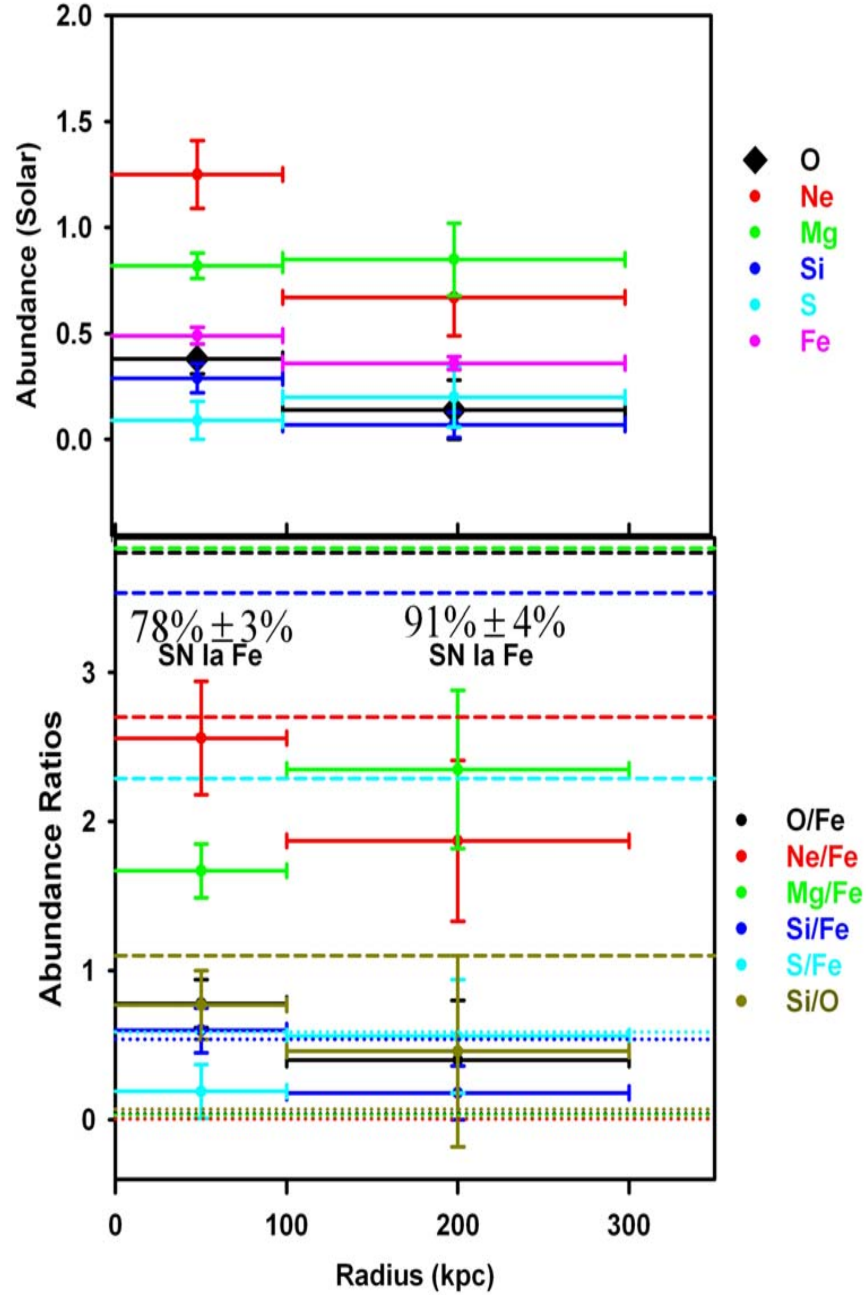
Temperature and Abundance profiles for the FGs are shown in the figure in this figure. Most FGs show a lack of cooling cores and some even show central temperature enhancements. The marginally significant central decline in temperature in RX J1416 may be due to anisotropies at ~200 kpc, since the temperature profile beyond that radius is consistent with the central values (Khosroshahi et al. 2006).
The Fe abundance profile is well constrained individually only for 2 FGs. No obvious global gradients correlations are found.



The analysis with improved statistics gained by joining all FGs shows a general central enhancement of α-elements and Fe (Top figure), suggesting an central excess of SN II dominance. This can be seen more specifically in the abundance ratio profiles (Bottom figure).

The values corresponding to 100% SN Ia (SN II) Fe mass fractions are indicated by dotted (dashed) lines for each specific ratio. In general, there is an enhancement of the ratios towards the center (more clearly seen in O/Fe, Ne/Fe, Si/Fe and Si/O).

Using an error-weighted average over all the ratios shown, we find that, despite the overall dominance by SN Ia of ~91% characteristic of the central regions of groups and poor clusters of galaxies, there is an unusual decline of the SN Ia Fe mass fraction towards the center of FGs (78%).



Summary

- The large velocity dispersion of FGs suggests that these systems have deep gravitational potential typical of poor clusters in agreement with the relatively high X-ray temperatures measured.
- We find a marginally significant (2.6σ) unusual enhancement of SN II Fe mass fraction in the central 100 kpc of FGs. The SN Ia Fe mass fraction is found to be 78% in that region increasing to 91% in the outer regions of these systems.
- This is consistent with a scenario where SN II powered winds resulting from merging late type galaxies erase the original central SN Ia Fe mass fraction dominance. This is also consistent with the recently found disky isophotes of the central dominant galaxies in FGs by Khosroshahi, Ponman & Jones (2006).
- Even though the lack of substructures, apparent “relaxation” and high concentration parameters suggest an early epoch for formation of FGs, the typical lack cooling cores and the central decline of SN Ia ejecta suggests that their formation (at least of the central cannibalistic merging) is posterior to that of normal groups. There are no obvious signs of strong AGN activity (such as bubbles) seen in the X-ray images of FGs in our sample. If an AGN mechanism is invoked to explain the FG characteristics, it should also be explained why it doesn’t work in regular groups.
- The small number of FGs observed have short exposures and this substantially limits the constraints that we can place on competing scenarios for the formation of these systems. A larger sample of FGs with medium exposures is a fundamental step to zero in on their nature and evolution.