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AN X-RAY AND OPTICAL ANALYSIS OF SUBSTRUCTURE**

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Abell 548: An X-ray and Optical Analysis of Substructure

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ABSTRACT

X-ray observations of Abell 548 reveal that the hot gas in this cluster is at least as complex as the galaxy distribution. Our *ROSAT* PSPC image is used in conjunction with optical data from the Minnesota plate scanning project and redshift data in the literature to investigate the degree of substructure in the intracluster medium and the galaxy distribution. A548 has several X-ray components: hot gas associated with clumps of galaxies, individual sources, and a newly discovered diffuse component. This diffuse component may be primordial gas falling into the cluster for the first time. The optical data suggest that this cluster consists of four major components, not three (as indicated when velocity data are ignored). Simple models of the orbital dynamics suggest that the cluster may not yet have reached its turnaround radius.

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1. INTRODUCTION

Clusters of galaxies can provide important constraints on models of structure formation, starting from the relatively featureless initial conditions in the early universe. In the most widely accepted current model (Cold Dark Matter, hereafter CDM), rich clusters are formed hierarchically, from mergers of smaller subunits. If a hierarchical model is valid and the universe is near the closure density, then we are living in the age of cluster formation (Richstone et al. 1992). Both optical (Geller & Beers 1982, Dressler & Shectman 1988a, Beers et al. 1991; Bird 1993, 1994) and X-ray (Jones & Forman 1992) observations demonstrate that at least some clusters (30-40%) are morphologically complex. This is generally interpreted as an indication that these clusters are still accreting less massive systems and therefore currently evolving. Several clusters are known to possess very lumpy morphologies (A1367, Bechtold et al. 1983; A400, Beers et al. 1992) and may be in the first stages of collapse. These systems provide a unique laboratory for studying cluster dynamics *before* virialization.

Abell 548 has a complex optical structure (Geller & Beers 1982, Dressler & Shectman 1988a) which extends over 2° , corresponding to $\sim 8h^{-1}$ Mpc at the redshift of the cluster ($H_0 = 50h$ km s $^{-1}$ Mpc $^{-1}$). A contour plot of the galaxy distribution reveals that the cluster is elongated and has at least two significant concentrations of galaxies. Its irregular structure is confirmed in the three-dimensional analysis of Dressler & Shectman (1988b). The single *Einstein* observation of this cluster is centered on the north-east clump of galaxies. This observation does not include the second concentration found by both Geller & Beers (1982) and Dressler & Shectman (1988a) and shows a single peak of X-ray emission which is smooth and fairly symmetric.

Here we present new *ROSAT* X-ray observations which cover a substantial fraction of the cluster, as determined from the galaxy distribution. This new image shows that the X-ray emission from the cluster is not confined to the regions with high galaxy density, but also occurs in a diffuse component. In conjunction with the X-ray data, we use a catalog of galaxies generated by the Minnesota Automated Plate Scanner to obtain a detailed optical map of A548 over the same area. This catalog, along with previously published spectroscopic redshifts, provides evidence that A548 is a cluster observed in the process of collapse, and is not yet dynamically relaxed.

2. X-RAY OBSERVATIONS AND OPTICAL DATA

The X-ray data for A548 were obtained using the *ROSAT* Position Sensitive Proportional Counter (PSPC) to observe four positions in cluster. The PSPC is sensitive to X-rays with

energy between 0.1-2.4 keV. and has a field-of-view of 2° . For sources in the center of the detector the spatial resolution is $\sim 25''$ (FWHM), although the resolution degrades towards the edges of the field. The PSPC also has moderate spectral resolution, which varies with energy as $\Delta E/E = 0.43(E/0.93 \text{ keV})^{-0.5}$. The *Einstein* IPC data for this clusters were obtained from the CD-ROM version of the *EINSTEIN* data set (Harris et al. 1990). The IPC observation was centered near the galaxy density peak we denote Clump A (see Table 4) and has a livetime of 10431 seconds.

The PSPC data for the central region this cluster were obtained over several months. The first portion of the observation was performed with no spacecraft ‘wobble’. Normal observations are made with the spacecraft pointing varied by several arcminutes, or wobbled, to reduce the number of sources obstructed by the PSPC window support structure (ribs). This first portion of data was also taken at two different roll angles, so the ribs appear to be multiple in the reconstructed image. The final ~ 4000 seconds of data were obtained at a third spacecraft roll angle. In this observation, however, the spacecraft was wobbled. Of the ~ 15 sources in the field, only one was significantly shadowed by the ribs. In our case this will not affect the analysis of the cluster, since any regions obscured in the central pointing are unobscured in our additional data. We obtained these additional PSPC data at three offset locations to determine the extent of the X-ray emission in A548. These additional fields are to the north-east, north-west and south-west and were chosen to overlap the central field. The pointing direction and the exposure times are listed in Table 1, along with the same information for the central PSPC field.

The digitized position and magnitude data were obtained from the first generation Palomar Sky Survey, using the Minnesota Automated Plate Scanner (MAPS) (Odewahn et al. 1992) to produce a catalog of galaxies within $1^\circ 5'$ of the central pointing position of the *ROSAT* field. The neural network classification software used to discriminate between stars and galaxies identified 796 galaxies in this field; subsequent visual verification of these objects, as well as calibration against the extensively-studied Coma Cluster, confirms that the catalog is 90% complete down to $m_b=20$. Because redshift information is not available for the majority of these galaxies, a cut in magnitude was used to eliminate foreground and background galaxies from the cluster sample. A548 is located at a redshift of 0.0414 (Dressler & Shectman 1988a), which corresponds to a characteristic photographic magnitude of 15. We accepted galaxies with approximate magnitudes between 12 and 17 as members of A548.

In their work on substructure in rich clusters of galaxies, Dressler & Shectman (1988a) provide velocities for 133 galaxies in the region of A548. Their target galaxies are taken from the Dressler (1980) catalog and cover a region of 2.1 deg^2 . This is unfortunately a somewhat smaller area than that included in the *ROSAT* observations, but still provides critical information about structure in this system.

3. X-RAY DATA ANALYSIS

3.1 Spatial Structure

Spatial analysis for these fields begins with determining the positions of the sources in the PSPC FOV. Source detection in the field was done with the COSMOS algorithm (Lutz 1979). The data for each of the four PSPC fields were corrected for vignetting effects. The background level of each of the four images differs, even in spatially coincident regions. These variations are most likely the result of Long Term Enhancements (LTE's) which were seen most clearly in the all-sky survey data. The LTE's are of unknown origin and vary on the timescale of days. They can contribute significantly to the measured background but are most prominent in the 0.11 to 0.28 keV spectral region. To correct for their effect, we compared the counts in overlapping regions for each of the data sets. Using the data set with the lowest absolute background count rate as the “true” background, we subtracted a constant from the other three fields so that all the fields have the same background. These fields were then coadded using their celestial coordinates to obtain the proper positioning. Examination of point sources in the overlap regions indicates that the positioning was accurate to within $15''$. This merged field was then smoothed with a Gaussian filter of $\sigma = 30''$. Figure 1 shows the contour map of this data. The northern and western portion of this map shows diffuse emission from the cluster. We can also see from this map that the diffuse emission is bounded and is not part of a larger structure on the sky.

We obtain an estimate of the background for this observation using the southeast portion of the field after excluding all point sources in the region. The entire field was then searched for peaks which are greater than 4σ above the background. The extended sources are listed in Table 2 along with the detected positions, PSPC count rate and X-ray luminosity in the 0.1 - 2.4 keV ROSAT band (assuming that they are at the distance of the cluster).

S1 is the only X-ray feature seen in the *Einstein* IPC observation of this cluster as well as our *ROSAT* observations. This X-ray feature is also spatially coincident with a prominent concentration of galaxies (see section 4 and table 5). The physical parameters, the core radius, central density and beta parameter, of many clusters observed with the *Einstein* IPC have been published (eg. Jones & Forman 1984). We will compare the physical properties of S1 as determined from the IPC data to those of other clusters also observed by *Einstein*. To do this, we must deconvolve the measured surface brightness profile from the IPC point spread function (PSF). The first step in this process is to estimate the contribution of the diffuse emission to the surface brightness. We produced a source profile with the diffuse emission included. We traced this profile until it flattened to an approximately constant value. This asymptotic value was taken to be the local background and subtracted from the surface brightness profile.

We must next model how the IPC PSF modifies the true surface brightness profile to produce what we observe. To achieve this, we use a modeling method similar to that used by Jones & Forman (1984). We generate a model surface brightness profile, convolve this with the IPC spatial response and compare this with the observed profile. We change the input model until the convolved model fits the observed profile. The goodness of fit is determined by computing the value of χ^2 to evaluate the input model. Using this method we find a core radius of $0.07^{+0.04}_{-0.03}$ Mpc, a central density of $3.24 \times 10^{-3} \text{ cm}^{-3}$, and a β value of $0.78^{+0.06}_{-0.05}$. This model fits the surface brightness of S1 with a reduced χ^2 value of 0.93 for 26 degrees of freedom. The core radius and central density are within the range of values given by Jones & Forman (1984) although the core radius is near the minimum found by those authors. The fact that these values are not unusual when compared to other clusters indicate that this component may be a relaxed system even in the midst of this large complex system. We cannot apply this method to fit the sources detected in the PSPC field since the point-spread function of the PSPC is not well calibrated for off-axis sources.

Extended emission is seen in these PSPC fields even after all sources are removed from the image. To remove the detected sources, we replace the counts in a circular region around each source by an average background level, determined from the annulus around the source to be deleted. Figure 2 shows the resulting diffuse emission, which is confined to the upper two-thirds of the northwestern portion of the field. It is elongated in the same direction as the galaxies in the Dressler & Shectman field (1988b, Figure 1). The average surface brightness of this diffuse component is $2.9 \times 10^{-4} \text{ counts s}^{-1} \text{ arcmin}^{-2}$. If this emission is associated with A548 then this is a previously undiscovered gaseous component. We have examined several possible origins for this diffuse component which are discussed below.

To determine if this extended emission is a local phenomenon we have examined the data set for evidence of enhanced particle background, increased localized soft X-ray flux and variability of this diffuse component and find no indications that any of these are present. Another possible source for this extended emission might be incomplete removal of sources or an incorrect background choice. To determine whether our choice of the radius to which to excise sources is the origin of the diffuse emission, we generated maps in which the radius of the replacement region was varied. To investigate the effect of the value used to “fill” the regions where we removed sources we also varied the replacement value for the excised regions. We used values from zero to the value determined within the background annulus to replace the counts from the source. While replacing counts in the source regions by zero created low regions or “holes” in the final maps of the diffuse emission, none of these methods changed its overall orientation or placement.

Another possible source for this diffuse emission is variations in the local emission from our galaxy’s interstellar medium. Variations in the interstellar medium are caused by local enhancements, eg. the north polar spur, or by absorption effects (McCammon & Sanders 1990).

Examination of the *ROSAT* all sky survey data (Snowden private communication) shows no large enhancement in the soft X-ray emission at the location of A548. Soft X-rays are strongly absorbed by neutral and molecular hydrogen. If either or both of these components are arranged to allow more soft X-ray flux from the ISM to be seen in the direction of the cluster this could be mistaken for cluster emission. It has also been shown (Low et al. 1984) that HI is often associated with infrared cirrus. This infrared cirrus is seen best in the IRAS 100 μ m maps of the sky. We have examined neutral hydrogen and IRAS 100 μ m maps of the region and these do not reveal any structure like that seen in the diffuse X-rays. Spectral evidence for the association of this component with the cluster is discussed in the next section.

3.2 Spectral Analysis

The limited spectral range of the PSPC (0.07 - 2.4 keV) makes the determination of most cluster temperatures difficult using PSPC data alone. Only when the cluster temperature is in or near the *ROSAT* bandpass can it be determined with precision. Most rich clusters of galaxies have temperatures which fall outside this spectral region (Mushotzky 1984). The variation of X-ray temperature T with cluster velocity dispersion σ_v has been investigated by Quintana & Melnick (1982) and Edge & Stewart (1991), and can be used to estimate the temperatures of systems with well-determined σ_v . Using *EXOSAT* and *Einstein* spectra Edge & Stewart find that

$$T = 10^{-3.22} \sigma_v^{1.35} \quad (1)$$

with T in units of keV and σ_v in units of km s^{-1} . In Section 4 below, we will find that the velocity dispersion of galaxies in optical Clump A, corresponding to S1, is $S_{BI} = 638 \text{ km s}^{-1}$. This velocity dispersion predicts an X-ray temperature of 3.7 keV, outside of the *ROSAT* bandpass. Therefore we fit not only the PSPC data by itself, but also combine it with the spectral data from *Einstein* and simultaneously fit both sets of observations. This allows an increase in the spectral range and a more precise determination of the temperature of the ICM.

3.2.1 Extended Sources

We fit the spectra from the *ROSAT* PSPC and the *Einstein* IPC and MPC for the brightest extended source in the cluster, S1. The spectral coverage of the IPC and MPC complement and extend the spectral range of the PSPC. We use IPC data covering the energy range from 0.5 to 3.0 keV which overlaps and extends the *ROSAT* PSPC spectral coverage which is from 0.1 to 2.0 keV. To further constrain the high energy portion of the spectrum we include MPC data covering the range from 1.2 keV to 11 keV. The MPC spectrum includes many of the weaker features seen near S1 in Figure 1. However S1 is much fainter than any of the other features and should dominate the MPC spectrum. Only the brightest peak in the *ROSAT* data was observed using the IPC, so this is the only feature for which we could perform simultaneous fitting for all three spectra.

The PSPC spectrum was extracted using a circular aperture with radius $7.5'$ centered on the peak of the X-ray emission of S1. The background was selected to be an annulus centered on the same position with an inner radius of $10'$ and an outer radius of $15'$. The background spectrum is corrected for vignetting after a model for the particle background has been subtracted. The particle contribution is added to the background spectrum after the vignetting correction. (This avoids the problem of amplifying the particle counts which are not vignettted.) This choice of background removes the local particle contribution as well as soft X-rays from the Galaxy. Unfortunately, this background determination may also include diffuse cluster emission. This might be avoided by using the background from one of the adjacent fields. However, obtaining a background spectrum from other PSPC fields has two major complications. One is the effect of LTE's which vary on a timescale of days. Even if two observations are taken sequentially, the use of one as a background field does not allow accurate removal of the LTE. One either leaves some of the photons from these events in your data or incorrectly removes some of the data. The second complication arises from the viewing geometry at which the two observations are obtained. The amount of scattered solar X-rays in a given field is a strong function of the angle between the target, the spacecraft and the earth. Unless the two viewing geometries are identical these scattered solar X-rays will not be properly removed from the data. Once these two effects can be accurately modelled, it should be possible to use our adjacent PSPC observations to model the background far from what we believe is the diffuse cluster emission. Until then we are restricted to using data from the same PSPC field to provide the background for our spectral fits.

The PSPC spectrum and best fit Raymond-Smith plasma model (Raymond & Smith 1977) are shown in Fig. 3. The temperature obtained is $2.48^{+5.01}_{-0.98}$ keV for a galactic HI column density of $N_{H^{gal}} = 2.08 \times 10^{20} \text{ cm}^{-2}$ (Stark et al. 1992). We also determined the iron abundance from the model spectrum, and find a lower bound of 5% solar with a best fit abundance of 1.06 solar. This yields $\chi^2 = 33.25$ with 29 degrees of freedom. All errors given here are 90% confidence intervals for one interesting parameter. Fixing the iron to 0.3 solar abundance and varying the value of galactic absorption does not significantly change the model's goodness-of-fit.

The IPC spectrum was extracted using the same area and centroid for the cluster and background as the PSPC spectrum for S1. Fitting a Raymond-Smith model to the IPC spectrum yields a lower bound of 1.9 keV for the X-ray emitting gas. The MPC spectrum is from a larger region ($45'$ square) around the cluster, which includes at least one other X-ray feature in A548 as well as the diffuse component, however the count rate from these sources is too low to significantly affect the MPC spectrum for S1. This spectrum is included in our fit to expand the spectral coverage and help constrain the temperature for this cluster. Figure 4 shows the best fit spectrum for the combined data sets for S1. The temperature we derive is $5.5^{+18.5}_{-2.6}$ keV using the galactic column density quoted above. This model yields $\chi^2 = 46.5$ for 43 degrees of freedom. Here we fix the metal abundance to the best fit PSPC-derived value, 1.09 solar.

For the remaining extended sources in the field we determined the radius to extract the source spectrum as outlined in section 3.1, by using the radial profile to determine the extent of the source. The background for the extended sources is taken from an annular region around each source after excluding all point sources in the annulus. We then fit the resulting spectrum to a Raymond-Smith plasma model. For these models we fixed the galactic column density at $2.07 \times 10^{20} \text{ cm}^{-2}$ and the abundance at 0.3 solar. We also fit the spectra while allowing the abundance to vary. The results of the fits for the PSPC data are shown in Table 3 as follows: 1) source number, 2) source radius, 3) radii for background annulus, 4) best fit temperature (keV) and formal 90% confidence intervals, 5) the abundance (solar units) and 6) χ^2 and the number of degrees of freedom (dof). S2 is the only extended source where the additional PSPC exposures resulted in a significant increase in exposure time. For this source we extracted the spectrum from both fields, corrected for vignetting and fit the spectra simultaneously. All spectra had at least 25 counts in each spectral bin so that the χ^2 statistic would be a valid measure of the goodness of fit.

3.2.2 Diffuse Cluster Emission

The spectrum of the cluster diffuse emission is extracted from the field center out to $10'$ from the edge of the PSPC field-of-view. The contribution of sources in the field is removed by excluding a $5'$ region around all the point sources, except for the extended sources, where we excluded a region of radius $7.5'$ from its center. The background is determined from a region in the southwest portion of the field and subtracted. The background spectrum is taken at 5:47:38.1 –26:11:55.4 and has an area of 225 square arcminutes while the source area is 2856 square arcminutes. The final spectrum is shown in Figure 5. Fitting this with a Raymond-Smith model yields a best fit temperature for the diffuse component of $0.73^{+0.26}_{-0.18} \text{ keV}$ (again using the Stark et al. N_H^{gal}), an emission integral of $2.4 \times 10^{67} \text{ n}_e \text{ cm}^6$, and the abundance is constrained to be less than 0.03 solar. The reduced χ^2 for this fit is 1.4 for 24 degrees of freedom. The confidence contours for the best fit model are plotted in Figure 6. Because the source spectrum is from a much larger area than the background spectrum, we also extracted a spectrum for the diffuse emission from within $20'$ of the center of the field. This reduces the effects of vignetting for the diffuse emission and we used the same background field as before. This fit yields a temperature of $0.75^{+0.36}_{-0.20} \text{ keV}$ and constrains the abundance to be < 0.08 solar at the 90% confidence level. As an alternative model a two temperature Raymond-Smith plasma model was fit to the data. If the abundance was constrained to be $0.2 < A < 1.0$ (consistent with the values found in rich clusters), the required temperature for the low temperature component is $0.15 < T < 0.21$, and no physically reasonable temperature could be found for the hotter component. Based on this we prefer the one temperature solution. We should also note that we have begun to study ~ 10 *ROSAT* PSPC fields to better understand the diffuse emission from our own galaxy. None of these spectra can be fitted with a single temperature Raymond-Smith plasma model with N_H^{gal} fixed at the measured value, and all are cooler than $\approx 0.24 \text{ keV}$ (see Wang and McCray 1993 for a similar analysis).

It is known that the soft X-ray background flux varies with position (McCammon et al. 1983).

We are currently investigating this variation in detail with *ROSAT* PSPC pointed observations. Preliminary results using ~ 10 fields at various galactic coordinates show that the temperature of the soft X-ray component is below 0.2 keV with solar abundance. The spectrum of the diffuse component in the A548 field is therefore considerably hotter than that observed in the local interstellar gas. The upper limit of the abundance of this diffuse component is 0.01 solar (90% confidence) and would be remarkably low for galactic emission. The spectrum from the background region used is well fit by a low temperature ($kT \sim 0.17$ keV) solar abundance Raymond-Smith plasma along with a power law component. This suggests that the background emission is primarily galactic in origin. This combination of spectral information and the alignment of this diffuse gas with the elongation of the cluster makes it highly unlikely that this diffuse component is of galactic origin. If this enhancement is of galactic origin this would be the first detection of a hot, $T \approx 0.9$ keV, cloud associated with our galaxy. On the other hand this diffuse emission has a temperature which is similar to the hot diffuse gas seen by *ROSAT* in the LMC (Trümper et al. 1991). Considering both the spatial and spectral information we associate this diffuse emission with A548. This component has an X-ray luminosity of 7.4×10^{43} erg cm $^{-2}$ s $^{-1}$, assuming that it is at the same distance as the cluster. While the luminosity of this component is comparable to that of a moderately massive cluster, its very low surface brightness makes its detection extremely difficult.

The PSPC observation of A548 reveals several pointlike sources embedded in the diffuse emission from the cluster. Several of these sources are close to optical galaxies in the cluster and, assuming that they are at the same distance as the cluster, have X-ray luminosities of $\sim 1\text{--}100 \times 10^{41}$ erg s $^{-1}$. A detailed analysis of these sources will appear in a later paper.

4. OPTICAL AND KINEMATIC ANALYSIS

The lack of spherical symmetry in the galaxy distribution, along with the clumpiness in the X-ray distribution, indicates that A548 is an extremely turbulent system. We have studied the X-ray and kinematic data on Abell 548 to compare the cluster’s X-ray and optical properties and to further probe its dynamical state.

To facilitate direct comparison with the *ROSAT* map of the intracluster medium in A548, we used the MAPS catalog to produce a contour map of the cluster smoothed optical luminosity. This map, Figure 7, was created using the adaptive kernel technique, introduced by Silverman (1986) and modified for application to clusters of galaxies by Beers et al. (1991). Unlike most earlier methods, which were either insensitive to significant features in the high-density regions of the galaxy distribution or overly sensitive to Poisson fluctuations in the low-density regions, the adaptive kernel technique uses a variable smoothing kernel to make the most efficient use of the available position data. The first pass through the dataset establishes a grid based on the total

number of datapoints. The second pass selects the smoothing size based on the local density of galaxies in the preliminary grid: larger in the outer, low-density areas and smaller in the inner, high-density areas. Significantly, the three largest peaks in the optical distribution are coincident with the main peaks in the diffuse X-ray emission. This lends support to the idea that A548 is an example of merging subclusters.

In their paper on substructure in rich clusters of galaxies, Dressler & Shectman (1988a) provide 133 velocities for galaxies in the region of A548. Their region of observation includes bright galaxies of all morphological types in the Dressler catalog (1980), but unfortunately not the entire area covered in the *ROSAT* map. We have proceeded with the dynamical analysis of this data pending further spectroscopic observations, in particular the galaxies associated with clump S3 do not have measured velocities. As members, we have accepted any galaxy within 3σ of the central location of the cluster, which is 12395 km s^{-1} before clipping. The final dataset includes all 133 galaxies, and has central location $C_{BI} = 12394 \text{ km s}^{-1}$ and scale $S_{BI} = 903 \text{ km s}^{-1}$.

To test for the significance of substructure in A548, we use a variety of one-, two- and three-dimensional substructure diagnostics presented in detail in Bird (1993) and summarized in Bird (1994). These are defined as follows: the skewness and kurtosis measure the symmetry and tail population of the cluster velocity distribution relative to a Gaussian (Fitchett & Merritt 1988; Bird & Beers 1993). The Lee statistic (Fitchett 1988) quantifies the probability that the position data were drawn from a two group parent distribution rather than a single group. The Δ -, α -, and ϵ -statistics (Dressler & Shectman 1988; West & Bothun 1990; Bird 1993, 1994 respectively) use velocity and position information simultaneously to look for substructure. The substructure diagnostics are normalized using a Monte Carlo resampling technique and 500 random realizations. By convention, in each of these tests the null hypothesis is rejected if the significance level is less than 0.100. That is, if less than 10% of the random realizations return a value of the test statistic which is greater than or equal to the value given by the observed distribution, we consider it a significant detection of substructure.

The only statistical diagnostic which *does not* reject the null hypothesis of no substructure, using the complete A548 dataset, is the skewness. This implies that the complicated velocity structure in this (at-least) bimodal cluster of galaxies is roughly symmetric. The kurtosis frequently rejects its Gaussian null hypothesis in cases where a velocity distribution is multimodal (cf. Ashman, Bird & Zepf 1994; Bird & Beers 1993). The Lee statistic is responding to the obvious dumb-bell distribution of galaxies on the sky. Similarly, the 3-D diagnostics all suggest that there is correlation between the velocities of galaxies and their positions which are inconsistent with a relaxed, well-mixed distribution.

Having shown that substructure is significant in this system, how do we identify the subclusters in A548? In order to identify members of subgroups objectively, having detected their presence using the preceding statistical tests, we have used a mixture modelling routine called

KMM (McLachlan & Basford 1988; Bird et al. 1992; Bird 1993). This routine simultaneously fits a user-specified number of Gaussians to the x - and y - projected positions as well as the radial velocity, iterating through all possible group assignments and selecting the best fit by maximizing the likelihood statistic. This algorithm requires an input guess as to the positions of the groups, their “size” (in terms of a covariance matrix), and a decision as to whether or not the groups have the same size or not. For this analysis, we have used group parameters estimated by eye from the optical contour map of the Dressler galaxies and the original velocity histogram. To help assure the stability of the solution, we forced the groups to have the same covariance matrix. We verified that the final results were not sensitive to the input parameters by changing these and repeating the analysis. As one would hope, the KMM algorithm converges to the same solution regardless of the input parameters, although the number of iterations required does vary. The details of the fitting are presented in Bird (1993). The algorithm is applied to a large database of cluster positions and velocities in Bird (1994).

Somewhat surprisingly, given the apparent bimodality in both the galaxy and gas distributions in A548, the *three* group fit is preferred to all other partitions. The first split that the algorithm makes is in position, as may be expected. But the southern clump is extremely dispersed in velocity, requiring an additional partition. Clump A is in the same position as the centroid of the brightest *ROSAT* X-ray peak (S1), which is located at R.A. $5^h46^m38^s$, Decl. $-25^\circ 29'30''$. The galaxies in clumps B and C are superimposed on the sky, with their separation being primarily in velocity space. This can be seen most clearly in Figure 9, where the histograms of Clump A (upper panel), Clumps B and C (middle panel) and B and C individually (left and right sides, respectively, of the lower panel) demonstrates the need for another partition in the group memberships. The position ellipsoids for the KMM groups are superimposed on the X-ray image in Figure 10. The positions of both Groups B and C are consistent with the X-ray centroid of the second *ROSAT* peak of extended emission (S2).

In Table 5 we present the statistical results and the mass estimators for the newly assigned groups. Note that although none of the subclusters possesses as many positive indications of structure as does the complete dataset (suggesting that the KMM algorithm has partitioned the galaxies sensibly), each of them does possess some structure. This may be due to unresolved structure remaining in the subclusters. Additionally, the KMM technique of assigning particles to groups is subject to error when the particle in question lies in the tails of its probability distribution. This effect may artificially truncate the velocity distributions of the subclusters and lead to a rejection of the Gaussian hypothesis by the kurtosis. Also in Table 5 we provide the members of the individual subclusters and their position centroids.

5. MASS ESTIMATES

The combination of X-ray spectral imaging data and galaxy dynamics allows us to determine

the mass of the components of the cluster using two independent methods. Assuming that the subclumps we have identified here are in hydrostatic equilibrium, using the temperature derived from the X-ray spectra and the surface brightness profile for the gas, we can obtain an estimate of the binding mass for each sub-clump.

Assuming that S1 is isothermal, that it extends to 7'5 (0.54 Mpc), and is in hydrostatic equilibrium with a temperature of 5.5 keV, equation 11b of Cowie, Henricksen and Mushotzky (1987) yields a total gravitating mass of $2.6^{+8.8}_{-1.2} \times 10^{14} M_{\odot} h^{-1}$, $\approx \frac{1}{3}$ of the total mass. Unfortunately, the PSF of the *ROSAT* PSPC is not well known off-axis. This precludes us from comparing the PSPC data with the IPC data for this clump and from deriving X-ray masses for the remaining extended sources discovered with the PSPC. The projected mass estimator (see below) for Clump A, when restricted to the same radius, yields a mass of $2.8 \times 10^{14} h^{-1} M_{\odot}$. The errors associated with the projected mass estimate can be quite large and are mostly from the uncertainty in the distribution of dark matter. Merritt (1987) has shown that extreme variations in the dark matter distribution can change the mass estimates by 0.4 to 300 times the actual value. Bird, Dickey & Salpeter (1993) estimate that the uncertainty in the dynamical mass due to substructure in the Hercules Cluster is at least 20%. Even with errors of 20% the optical and X-ray mass estimates are in good agreement.

In Table 4, we have also provided the dynamical mass estimates for the optical clumps in A548, the virial theorem mass estimator (c.f. Bird et al. 1993), the projected mass estimator (Heisler et al. 1985) and the robust virial theorem estimator (Beers et al. 1991). This table includes the mass estimators for the cluster as a whole, as well as masses determined for the individual clumps. The mass obtained by summing the masses of the three groups from the projected mass estimate, is $M = 20.6 \times 10^{14} M_{\odot}$. This is similar to the mass of the Coma cluster, a much hotter and more luminous system. This is $\sim 70\%$ of the mass obtained by using all the velocity information without the division into subclumps (Table 3) and this fraction does not depend on which mass estimator we use.

6. DISCUSSION

The CDM paradigm of structure formation indicates that structure is formed from the bottom up. In this picture, small units are formed early in the history of the universe, and by their mutual gravitational attraction form larger structures. This hierarchical formation of structure continues until the largest known bound structures are formed, clusters of galaxies. Evidence that this process continues to the present epoch is found in two rich clusters, Coma (A1656) and A2256. A1656 shows evidence for substructure in the ICM in both the outer and inner regions (Briel, Henry & Bohringer 1992; Davis & Mushotzky 1993; White, Briel & Henry 1993). The galaxy distribution in the central region of the Coma cluster is also bimodal (Fitchett & Webster

1987, Mellier et al. 1988), and the velocity distribution for those galaxies is somewhat flatter than Gaussian (Fitchett & Merritt 1988). X-ray observations of A2256 reveal a cool lump of gas projected near the core of this cluster (Briel et al. 1991). Statistical diagnostics of structure (Bird 1993; also Briel et al. 1991) reveal correlations between velocities and positions of galaxies in A2256, as expected for merging subclusters. Features in the predominantly smooth X-ray distributions of these clusters are thought to indicate the infall of galaxy groups into the deep gravitational potentials of these otherwise relaxed clusters.

N-body simulations of cluster formation show that the collapse of the primordial matter overdensity to a centrally concentrated cluster occurs in several stages. In the early part of the collapse, the proto-cluster forms from the coalescence of subgroups of comparable mass. These continue interacting to produce a smooth galaxy and gas distribution. A548 may be a perfect example of such a system since it shows multiple peaks in its distribution of both gas and galaxies. It also possesses a diffuse gas component.

For two point masses to be gravitationally bound, their gravitational potential energy must exceed their mutual kinetic energy. This forms the basis of the two-body Newtonian binding criterion:

$$M_{sys} v^2 \leq \frac{GM_{sys}^2}{R} \quad (2)$$

Here M_{sys} is the combined mass of the two bodies, v is their three-dimensional relative velocity, and R is their separation in physical space. We relate these quantities to the observed values by letting α be the angle that the axis of the two-body system makes with the sky. Then $v_{los} = v \sin \alpha$, $R_p = R \cos \alpha$ and the two-body binding criterion becomes:

$$\frac{v_{los}^2 R_p}{2GM_{sys}} \leq \sin^2 \alpha \cos \alpha \quad (3)$$

Figure 11 provides the distribution of $\sin^2 \alpha \cos \alpha$ for angles between 0° and 90° . In observational units,

$$11.27 \frac{v_{los}^2 C_{BI} R_p''}{M_{sys}} \leq \sin^2 \alpha \cos \alpha \quad (4)$$

with velocities in km s^{-1} and M_{sys} in solar masses. This inequality defines a range of α for which any two subclusters are bound. We refer to the quantity on the left-hand side of Eq. 4 as the *binding ratio* for a given pair of masses.

Although A548 is more complicated than a simple two-body system, application of this naive criterion to pairs of subclusters may provide insight into the cluster's dynamical structure. The binding ratio for Clumps A and B is 0.709, indicating that they are not gravitationally bound for any value of α . For A and C, the binding ratio is 0.094, and these subclumps are bound for values of α_{AC} between 20° and 80° . Clumps B and C have a binding ratio of 0.272 and are only bound if α_{BC} is between 35° and 70° . These calculations suggest that Clumps A and C are the

primary components of A548, and that Clump B is not physically associated with the cluster. This complexity is not detectable in the velocities, galaxy distribution, or X-ray image considered independently.

Numerical simulations of bimodal clusters show that if the two subclusters are gravitationally bound, then they merge on a timescale on the order of the orbital period (about twice the free fall time) (Gelato, Chernoff & Wasserman 1992). Using the total mass from Table 4 and assuming the cluster radius extends to the edge of the central PSPC field-of-view, $4.3h^{-1}$ Mpc, then the free fall time is $\sim 5 \times 10^9 h^{\frac{2}{3}}$ years. The gas temperature of the final collapsed cluster can be estimated by assuming the gas kinetic energy is in equilibrium with the cluster potential energy:

$$\frac{3}{2} \frac{kT_{gas}}{\mu m_p} = -\phi \quad (5)$$

Using the subclump masses to estimate the gravitational potential, this yields a gas temperature ~ 8 keV. While this simple calculation should overestimate the gas temperature since it ignores any cooling terms, it agrees well with the temperatures seen in other systems with similar total mass, such as Coma.

What observational evidence (other than the two-body argument) implies that this collection of galaxies is gravitationally bound? The X-ray temperature of the gas associated with the brightest subclump, A, is consistent with that predicted using the σ_v -T relation (Edge & Stewart 1991, Mushotzky 1984). The best fit temperature, $5.5^{+18.5}_{-2.6}$ keV, is consistent with the temperature estimated from equation 1, 3.7 keV (where we use S_{BI} for Clump A as a measure of σ_v). The discovery that Clumps B and C are kinematically distinct brings the predicted X-ray temperature using S_{BI} for either clump using equation 1 in agreement with the measured temperatures. While these spectral fits do not tightly constrain the temperature, they are consistent with the hypothesis that Clump A has virialized before the cluster as a whole and that either clump B or C is also in viral equilibrium. This supports theoretical predictions and numerical simulations which show that subclumps in the protocluster relax before the entire cluster collapses and virializes. If the cluster has collapsed and these subclumps are remnants of the process, then the diffuse component of the ICM should also be in equilibrium with the cluster potential. As we have seen, this predicts a gas temperature of ~ 5.9 keV, but the temperature we measure is 0.73 keV. Thus, this low temperature implies that the diffuse gas cannot be thermally supported against collapse and should be falling into the cluster.

The abundance of metals in the different components of the cluster also help constrain the history of A548. The gas in Clump A, S1, has a best fit abundance of 1.09 solar. (However, it should be noted that these data only constrain the abundance to be greater than 0.05 at the 90% confidence level.) If this abundance is confirmed it indicates the gas in Clump A has undergone considerable enrichment. The X-ray spectra for S2 and S3 also show that it is likely that these objects also have been enriched with metals although not to the same degree as S1 if the best fit

spectral values are validated. Initially metal poor gas may be enriched by gas injected into the ICM by galaxies undergoing bursts of star formation. David et al. (1991) calculate the efficiency of this process. They show that significant quantities of metals can be injected into the cluster gas from the early evolution of young galaxies. Merger events between galaxies in the cluster may shock heat gas and allow it to escape into the ICM, thereby providing another source of metal enrichment. The metal abundance of the extended sources have values consistent with other clusters of galaxies which may imply that some of their gas had its origin in the galaxies. This is in opposition to the diffuse gas, which has extremely low metal abundance, has not been enriched and may be falling into the cluster for the first time.

We can obtain an average density for this diffuse component of the cluster using the emission integral from the spectral fit, Section 3.2, and assuming a shape for the emitting gas. Given the elongated shape of the cluster we choose a cylindrical volume with a length of 2° ($8.7h^{-1}$ Mpc) and a radius of 0.75 ($3.3h^{-1}$ Mpc). Using these assumptions we find the the average electron number density is $\sim 9.0 \times 10^{-4} \text{ cm}^{-3}$. This is lower than is seen in the central regions of most clusters (Jones & Forman 1984). In contrast to rich clusters the diffuse gas has a best fit abundance of zero, or no metals. Recent observations with Ginga (Hatsukade 1989) show that the iron abundance in clusters decreases with increasing X-ray luminosity. Using the luminosity of the diffuse component the Ginga data would predict a measured iron abundance of ~ 0.5 solar. The only other example of hot gas with such low abundance is the diffuse gas in the NGC 2300 group (Mulchaey et al. 1993). This low abundance in cluster gas is quite unusual and follow up studies are needed to confirm this low value. If this low abundance is verified, then we may be observing primordial gas which is falling into the cluster potential, consistent with the hypothesis that Abell 548 is dynamically young.

7. CONCLUSIONS

Both X-ray and optical observations reveal that Abell 548 has a complex morphology. The X-ray image of the cluster has several components: 3 lumps of extended emission, several point sources and a newly discovered diffuse component. The extended X-ray sources are associated with clumps of galaxies. There are three physically distinct optical structures found in the kinematic data, two of these are superimposed along the line-of-sight. The dynamics of the hot gas and galaxies indicates that at least some portions of this cluster have begun to collapse and virialize.

Optically, A548 possesses at least 4 statistically significant subclumps. Clump A is coincident with the brightest X-ray peak, S1, which has a temperature and luminosity consistent with the X-ray to optical correlations derived by Edge & Stewart (1991). This suggests that this subclump is virialized. The best fit metal abundance of S1 also argues that, at least if the metals are coming from star formation in the galaxies, considerable interactions between the galaxies and the ICM must have occurred. This also supports the claim that this subcluster is dynamically evolved.

Some of the other point sources can be associated with galaxies in the cluster and have X-ray luminosities similar to those found for galaxies in A1367 (Bechtold et al. 1983) and A2256 (Henry & Briel 1992).

The newly discovered diffuse component seen in this cluster has a low X-ray temperature and extremely low metal abundance. Therefore we suggest that this may be primordial gas which is collapsing into the cluster (as opposed to gas ejected from the galaxies in the cluster). The extent of this diffuse gas is $\sim 8 h^{-1}$ Mpc.

The combination of X-ray and optical data indicates that A548 is a cluster in the process of formation. Simple arguments show that the final state of this cluster should have an X-ray temperature close to that seen in other rich clusters. Our optical data show that this cluster extends beyond the region surveyed by Dressler (1980). For instance, we see three clumps of galaxies to the southeast (Fig. 7). Inspection of Fig. 1 shows that there is X-ray gas associated with the largest of those clumps of galaxies. We are in the process of obtaining optical spectra of the galaxies outside the previously studied region and plan to combine this with our additional *ROSAT* PSPC observations.

We would like to thank Keith Arnaud for help with the data analysis and for his critical reading of the text and Steve Snowden for kindly allowing us access to the *ROSAT* all sky survey images. We would also like to thank A. Edge, for his helpful comments and careful reading of the manuscript and we would also like to thank our anonymous referee.

TABLE 1
Rosat PSPC Fields

Seq. #	R.A. (J2000)	Dec. (J2000)	Exposure seconds	Observation date
800041	5:46:00	-25:46:12	4041	Feb 21-23 1991
800041	5:46:00	-25:46:12	3913	Mar 5 1992
800289	5:49:00	-25:00:00	1652	Mar 1-2 1992
800290	5:44:24	-25:55:48	5058	Sep 26-27 1992
800291	5:43:00	-24:43:48	3172	Feb 24 1993

TABLE 2
Extended Sources Detected in the Abell 548 Field

No.	R.A. (J2000)	Dec. (J2000)	Count Rate	L_x $\times 10^{43}$
1	5 48 40	-25 28 30	0.36 ± 0.01	2.67 ± 0.11
2	5 45 35	-25 52 15	0.17 ± 0.09	1.26 ± 0.70
3	5 42 08	-26 07 38	0.27 ± 0.01	2.00 ± 0.12

TABLE 3
PSPC Spectral Results for the Extended Sources

No.	Source radius	Background radius	kT	A	χ^2/dof
S1	7'5	10'- 15'	$3.58^{+20.0}_{-2.07}$	0.3	35.3/30
			$2.48^{+5.01}_{-0.98}$	>0.1	33.2/29
S2	7'5	10'- 15'	$2.65^{+1.92}_{-0.88}$	0.3	40.5/51
			$2.64^{+2.55}_{-1.01}$	0 - 0.9	40.5/50
S3	12'	15'- 20'	$1.57^{+0.88}_{-0.32}$	0.3	26.0/25
			$1.58^{+1.18}_{-0.33}$	0.1 - 0.6	26.0/24

TABLE 4
Diagnostics for A548 Complete Dataset

$C_{BI} \text{ km s}^{-1}$	12394	
$S_{BI} \text{ km s}^{-1}$	903	
Statistical Test	Value	Signif. Level
Skewness	0.199	
Kurtosis	-0.860	0.010
Lee	2.878	<0.001
Δ -test	0.885	< 0.001
α -test	434.3''	0.006
ϵ -test	0.821	<0.001
Mass Estimator	Mass ($10^{14}h M_{\odot}$)	
Projected Mass Estimator	29.8	
Virial Theorem	21.2	
Robust Virial Theorem	23.4	

TABLE 4
Diagnostics for A548 Subclusters

Clump A–X-ray Source S1		
N_{gal}	56	
R.A.	05:48:41	
Decl.	–25:26:55	
C_{BI} (km s ^{–1})	11967	
S_{BI} (km s ^{–1})	638	
Statistical Test	Value	Signif. Level
Skewness	0.179	0.274
Kurtosis	2.117	0.026
Lee	1.486	0.562
Δ -test	0.239	0.420
α -test	293.1''	0.070
ϵ -test	0.382	0.502
Mass Estimator	Mass ($10^{14}h M_{\odot}$)	
Projected Mass Estimator	8.6	
Virial Theorem	6.8	
Robust Virial Theorem	7.6	
Clump B		
N_{gal}	52	
R.A.	05:45:40	
Decl.	–25:50:23	
C_{BI} (km s ^{–1})	13209	
S_{BI} (km s ^{–1})	553	
Statistical Test	Value	Signif. Level
Skewness	0.211	0.246
Kurtosis	2.674	0.418
Lee	2.577	0.010
Δ -test	0.269	0.450
α -test	320.1''	0.038
ϵ -test	0.362	0.358
Mass Estimator	Mass ($10^{14}h M_{\odot}$)	
Projected Mass Estimator	8.4	
Virial Theorem	4.8	
Robust Virial Theorem	5.0	

TABLE 4 cont.

Clump C		
N_{gal}	25	
R.A.	05:45:31	
Decl.	−25:57:47	
C_{BI} (km s ^{−1})	11608	
S_{BI} (km s ^{−1})	422	
Statistical Test	Value	Signif. Level
Skewness	0.308	0.232
Kurtosis	2.722	0.570
Lee	3.320	0.286
Δ -test	0.138	0.306
α -test	556.6"	0.124
ϵ -test	0.871	0.458
Mass Estimator	Mass (10 ¹⁴ h M _⊙)	
Projected Mass Estimator	3.6	
Virial Theorem	3.0	
Robust Virial Theorem	3.6	
Subcluster Assignments		
Clump	Dressler-Shectman ID of Members	
A	86,88,90,91,100,101,107,108,109,112,116,122,123,125 134,135,136,137,138,142,144,145,153,154,155,157,158,159 161,168,170,171,172,173,174,177,178,179,180,182,183,186 187,191,193,194,196,199,207,208,212,213,214,216,217,222,226	
B	4,7,13,14,16,17,26,33,39,40,41,42,43,45,46,47,48,49,51,52 54,60,64,65,66,68,70,71,79,81,84,85,92,94,99,102,104,105,117 118,119,127,128,130,131,149,150,151,175,200,203,228	
C	5,8,11,12,18,19,20,21,22,25,32,36,38,56,57,67,72,76,77,78 82,83,97,98,167	

Positions given are epoch 2000.0

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Figure Captions

Figure 1: A contour map of the PSPC image of the Abell 548 cluster. The central portion of the four coadded PSPC fields are shown with a pixel size of $\sim 15''$ and smoothed using a gaussian with a sigma of 2 pixels. The brightest feature seen to the northeast is the X-ray feature found using the EO IPC. In the northwest portion of the field the diffuse emission can be seen. The two bright sources outside the circular ribs (radius $\sim 20'$) in the western half of the field are point sources. The contour levels are 0.87, 1.05, 1.27, 1.54, 1.86, 2.24, 2.71, 3.28, 3.96, 4.79, 5.79, 7.00 counts per pixel.

Figure 2: A greyscale map of the diffuse emission with contours of the diffuse emission overlaying the greyscale image. The contour levels are (1.14, 1.06, 0.99, 0.93, 0.86, 0.80, 0.75, 0.70) $\times 10^{-3}$ counts s^{-1} . The large circles denote the edges of the PSPC fields and the small circles are where sources have been removed before smoothing the residual image with a $4'$ gaussian.

Figure 3a: The ROSAT PSPC spectrum for the X-ray feature in Fig. 1, which we denote clump A in the text. This is the same X-ray feature seen in the EO IPC. The best fit model (solid line), with N_h fixed at the galactic value and folded through the detector response, is drawn with the data.

Figure 3b: The residuals from the best fit model in Fig 3a.

Figure 4a: Here we show the ROSAT PSPC spectral data along with the EO IPC and MPC data for clump A. The solid lines are the best fit to the data folded through the individual detector response.

Figure 4b: The ratio of the model and the data are shown here.

Figure 5a: The spectrum of the diffuse emission seen the in Abell 548. All detected sources were excluded from the data as described in the text and the background for this spectrum was taken from the southeast portion of the field. The data point a 0.6 keV was removed from the fit because three channels in the 256 channel spectrum were anomalously low. This was too narrow to be a real feature in the PSPC so the data point was removed.

Figure 5b: The residuals for the fit shown in fig. 5a.

Figure 6: A contour map showing the Raymond-Smith model fitting parameters in the abundance-kT plane. The 68%, 90% and 99% confidence contours for two parameters are shown.

Figure 7: A contour map of the smoothed galaxy distribution. The galaxy distribution has been smoothed using the adaptive kernel technique. The contour levels are 0.0342, 0.0671, 0.100, 0.1329, 0.1658, 0.1987, 0.2316, 0.2645, 0.2974, 0.3303 galaxies per arcmin². The map is centered at 05:44:53.4 –25:42:01 (J2000). The bar in the lower right hand corner has a length of 1.45 Mpc.

Figure 8: The velocity histogram of all the galaxies in the Dressler-Shectman data set for Abell 548.

Figure 9: The velocity histograms for the subgroups identified by KMM. Clump A (*upper panel*) ; Clumps B and C combined, showing the need for an additional partition (*middle panel*) ; Clump B (*lower panel, left*); Clump C (*lower panel, right*). In each case, the velocity range is 10000–15000 km s^{–1}.

Figure 10: The 95% confidence ellipses for the positions of the subgroups identified by KMM within A548. There are superimposed on the *ROSAT* X-ray map to demonstrate the success of KMM at resolving physically distinct systems.

Figure 11: A graphic representation of the two-body Newtonian binding criterion. The right-hand of Eq. 1, $\sin^2 \alpha \cos \alpha$, is plotted against α , the angle that the axis of the two-body system makes with the plane of the sky.

Fig 1

Figure 2

Fig 3a

Fig 3b

Fig 4a

Fig 4b

Fig 5

data and folded model

Fig 6

Abell 548

Figure 7

Fig 8

Fig. 9

Fig. 10

Fig. 11