SUBCLUSTER MERGERS AND GALAXY INFALL IN A2151

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Abstract

We have obtained a 12.5 ksec image of the Hercules Cluster, A2151, with the *ROSAT* PSPC. Comparison of the optical and X-ray data suggest the presence of at least three distinct subclusters in A2151. The brightest X-ray emission coincides with the highest-density peak in the galaxy distribution, and is bimodal. The northern subclump, distinct in position and velocity, has no detectable X-ray gas. The eastern subclump, apparent in the optical contour map, is indistinguishable from the main clump in velocity space but is clearly visible in the X-ray image.

X-ray spectra derived from the central peak of emission yield a best-fit temperature of 1.6 keV. The emission coincident with the eastern clump of galaxies is cooler, 0.8 keV, and is outside the 90% confidence intervals of the central peak temperature.

We suggest that the eastern and central subclusters have recently undergone a merger event. The lack of X-ray emission to the north suggests that those galaxies do not form a physically-distinct structure (i.e. they are not located within a distinct gravitational potential), but rather that they are falling into the cluster core along the filament defined by the Hercules Supercluster.

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1. INTRODUCTION

The early assumption that most clusters of galaxies are relaxed has proven to be incorrect. X-ray imaging observations with the *Einstein* satellite first revealed that complexity in the intracluster medium (ICM) is frequent (Forman et al. 1981; Henry et al. 1981), in contrast to the smooth configurations assumed in early studies (cf. Kent & Gunn 1982; Kent & Sargent 1983). Since then, both optical (Geller & Beers 1982; Baier 1983; Beers et al. 1991; Bird 1993, 1994a,b) and X-ray studies (Jones & Forman 1992; Davis & Mushotzky 1993; Mohr, Fabricant & Geller 1993) have revealed that many, if not all, clusters possess significant deviations from an equilibrium state. Peculiar velocities of brightest cluster galaxies, in particular the ultraluminous cD galaxies once thought themselves to be signatures of advanced dynamical evolution, are correlated with the presence of substructure (Bird 1994b). The properties of radio galaxies are dependent on their local physical environments, not their global cluster properties (Burns et al. 1994). Observations of clusters in all wavebands reveal that dynamically-relaxed, spherical systems seem to be the exception rather than the norm.

In many massive clusters of galaxies, the morphologies revealed by either galaxies or gas are similar. For instance, in the Coma Cluster (A1656), the *ROSAT* PSPC image verifies the gravitational integrity of the southwestern clump of galaxies, which is not clearly distinguishable in velocity space (White et al. 1993; Bird 1993). In this sense X-ray and optical observations complement each other well. The ICM is a sensitive tracer of the gravitational potential, but cannot reveal (with current techniques) the presence of structure along our line-of-sight to a cluster. Velocity data from optical or radio spectra can distinguish systems superimposed along the line-of-sight, but yields little information about subcluster mergers in the plane of the sky. Therefore, in order to understand the dynamical state of
any particular cluster it is helpful to combine X-ray and optical observations.

A2151, the Hercules Cluster, is the prototypical rich, irregular cluster of galaxies. Its high spiral fraction, \( \sim 50\% \), makes it an attractive target for 21-cm. radio observations. For example, Bird, Dickey & Salpeter (1993, hereafter BDS) supplement the optical catalog of redshifts using neutral hydrogen observations of faint spirals. BDS find evidence for a significant level of substructure in A2151, verifying earlier detections by Geller & Beers (1982), Dressler & Shectman (1988) and West & Bothun (1990). In particular, BDS note that there is some contradiction between these optical results, which find subclusters separated by about 17 arcminutes on the sky, and the X-ray results of Magri et al. (1988; hereafter M88). Their *Einstein* IPC image of A2151 is clearly bimodal, but the peaks of X-ray emission are separated by only about seven arcminutes. The emission detected by *Einstein* is confined to the central, highest density galaxy peak. BDS proposed that the gas density in the other optically-identified subclusters is too low to be detected by the IPC.

We have obtained a 12.5 ksec observation of A2151 with the *ROSAT* PSPC. The sensitivity of the PSPC to low surface brightness features and its large field of view enable us to directly compare the large-scale morphology of the gas and galaxy distributions in this spiral-rich irregular cluster. The PSPC image reveals that, unlike the case in Coma and most other clusters, the gas and galaxy morphologies in A2151 are very dissimilar. The long integration time also makes it possible to compare temperature and metallicity estimates in different regions of the cluster.

In Section 2, we present the reduction and analysis of the *ROSAT* image and spectra. In Section 3, we use the information derived from the X-ray image to constrain the analysis of the optical and 21-cm redshift catalog from BDS. We have supplemented their velocity and position data with morphological types taken from the Dressler (1980) catalog. This
additional information allows us to look for variations in spiral fraction and kinematic differences between ellipticals and spirals, which may correlate with properties of the ICM (M88; Zabludoff & Franx 1993). In Section 4 we present a summary of the A2151 observations and our interpretation of its dynamical state.

2. X-RAY OBSERVATIONS

2.1 Image Analysis

The ROSAT PSPC (Position Sensitive Proportional Counter) is a wide-field imaging instrument. Its large field of view (2° across) and sensitivity to extended, low surface brightness emission make it an obvious choice for imaging clusters of galaxies. The PSPC has a FWHM of 30" in the central 40 arcmin of the field of view, which is equivalent to approximately $21h^{-1}$ kpc at the recessional velocity of the main Hercules subcluster (see below). Here $H_0 = 75h$ km s$^{-1}$ Mpc$^{-1}$. The resolution degrades toward the field edges to several arcmin, which is about $100h^{-1}$ kpc. The front window of the X-ray detector (which is protected by a fine wire mesh) is supported by a ring and axis support. These supports block incident X-rays and project a shadow onto the detector. This shadow can be seen on the detector as a circular feature with a radius of 20′ in the center of the detector with 6 radial supports, which leaves the central 40′ of the detector clear of obstruction. To smooth out the effects of the wire mesh, the satellite is wobbled during the observation to provide even exposure over most of the field of view.

We have performed our image and spectral reductions using the Post-Reduction Offline Software (PROS) within the IRAF environment, and XSPEC to fit spectral models. In order to minimize the effects of solar X-rays, which illuminate the detector after being scattered by the earth’s atmosphere, we first screened the data using the total Accepted X-ray Events (AXE) count rate as our discriminator. By smoothing the AXE and eliminating
times where the count rate exceeded $2\sigma$ above the mean, we can eliminate most of the scattered solar X-rays from our dataset. This procedure eliminated about 400 seconds of the observing time, or 3.2% of the total time. The A2151 image was corrected for vignetting using exposure maps derived within the 7 energy bands of the PSPC as defined by Snowden et al. (1993). The effective exposure maps in these 7 bands are generated using software at Goddard Space Flight Center and are based on the precise orientation of the satellite during the observation. Having used these energy-dependent exposure maps for flatfielding, we then co-add the images in the 0.5-2.0 keV energy range. Excluding the low-energy photons reduces contamination by galactic X-ray emission and reduces the effects from the long term enhancements (Snowden et al. 1992). The background for the spatial analysis is taken from our dataset using the northwestern area of the image. This region is an 11.5′ circle centered at $\alpha(J2000.0) = 16:02:55$, $\delta(J2000.0) = +18:02:40.3$, well outside of the central region of emission. Visual inspection shows that this area is devoid of cluster-related emission or point sources. In the background region the count rate is 0.3 counts/pixel, which in physical units is $3.96 \times 10^{-4}$ counts/s/arcmin$^2$. The flattened, background-subtracted image is smoothed with a 30″ Gaussian filter and shown in Figure 1.

Examination of Figure 1 reveals the presence of many point sources coincident with the cluster. In a forthcoming paper we will present an analysis of these serendipitous sources, which for the most part are coincident with optical galaxies. We do not include them in the rest of this study.

Comparison of the PSPC image with the corresponding optical image and galaxy number density contours in Figure 2 (optical image provided by A. Dressler; contour map taken from BDS) reveals that in this complicated galaxy cluster, the X-ray and optical distributions are not very similar. This is unlike either A1656 (White et al. 1993) or A548 (Davis et al. 1993),
two systems of different morphology in which the galaxies and ICM trace each other closely. The bimodal structure seen in the core of A2151 by M88 is clearly seen in the ROSAT image. This complexity in the ICM is not obviously related to any similar structure in the galaxy distribution, as comparison with Figure 2 reveals.

To verify that these sources are extended, we compared the measured point spread function of the PSPC to the profile for the sources. To do this we extract the radial profile for the sources listed in Table 1 in the energy range from 0.5 keV to 2.0 keV. The profile was fit using software included with the FTOOLS software package. The modelled PSF is a good fit for the measured profile for A2151N only. To quantify this, we list the measured half power radius for the sources in A2151. The predicted half power radii are for point sources having the same spectral distributions and off-axis angles as the A2151 sources. We find that both sources in the central region (designated as A2151C (bright) and A2151C (faint) in Table 1) and A2151E have half power radii which are far larger than the PSF:

| Source       | Half-power radius (") | Predicted |
|--------------|------------------------|-----------|
| A2151C (bright) | 101                    | 24        |
| A2151C (faint)  | 36                     | 14        |
| A2151E         | 195                    | 30        |

On the other hand, the northern source is point-like, with an observed half-power radius of 72" and a predicted value of 66". Because the central and eastern sources are extended, we assume that their emission is originating in the intracluster medium.

The northern subcluster, first identified by BDS on the basis of its position and kinematics, has no diffuse X-ray emission associated with it, at an upper limit of $1.19 \times 10^{-3}$ counts/s/arcmin$^2$ (the flux limit is $1.2 \times 10^{-14}$ erg/s/cm$^2$). The point source in the northern subcluster has a power-law spectrum (see next section) and is located at the position of NGC 6061. NGC 6061 is listed as a radio-galaxy in the catalog of Zhao, Burns & Owen (1989). We tentatively identify it as an active galaxy although it is not listed in the AGN catalog of
Veron-Cetty & Veron (1987). We have been unable to find any optical spectra of this galaxy to verify this identification.

The eastern galaxy enhancement, which was noted but could not be verified by BDS on the basis of its velocity distribution, does appear in the X-ray map. Its spatial extent, the coincidence of its position with the optical peak and its spectral characteristics (see next section) suggest that it is physically associated with the subcluster. This in turn suggests that the subcluster itself is physically distinct from the central gas and galaxy peak.

### 2.2 Spectral Analysis

The PSPC spectral properties are unfortunately not quite as appropriate for clusters as its imaging capabilities: the PSPC detects individual X-ray photons in the energy range 0.1-2.4 keV, with a resolution of \( \frac{\Delta E}{E} \sim 0.4 \left( \frac{E}{1\text{ keV}} \right)^{-1/2} \). This energy range is somewhat lower than the typical emission weighted mean temperature for rich clusters, 5-6 keV (Mushotzky 1984). The M88 observations of A2151 show that its ICM is cooler and less luminous than is usual for a rich cluster, so the PSPC nonetheless should enable us to constrain the spectral properties of the Hercules system.

We select four areas of our A2151 image for spectral modelling: the two peaks seen near the cluster centroid (these were detected in the *Einstein* image), the eastern emission, and the bright northern source. We extracted these regions from the broadband image using the PROS utility ‘qpspec’. The contribution of unrejected charged particles was modeled using the average master veto rate and removed from the extracted spectra. The background spectrum was extracted from the same region used in the image analysis. We used the XSPEC package (Shafer et al. 1990) for the model fits. For each of the 4 regions we tested two different models, a Raymond-Smith plasma (for thermal emission from the ICM) and a
power-law spectrum (typical of active galactic nuclei). In addition, to verify that our spectral fits were not adversely affected by the presence of more than one temperature component in the emission, for the central regions we tested two-temperature models as well as the single component description. The individual fits are discussed below.

The relatively narrow energy bandpass and resolution of the PSPC mean that, rather than determining temperatures and metallicities directly from line ratios as is done with optical spectroscopy, the shape of the X-ray spectrum is used to estimate the physical properties of the system being studied. This strategy works well for cool clusters, in which the peak temperature is either within or at least close to the *ROSAT* bandpass. For the brightest X-ray peak, a Raymond-Smith plasma with temperature $1.67^{+0.47}_{-0.25}$ keV and metallicity $0.56^{+0.31}_{-0.20}$ solar produced a $\chi^2 = 24.92$ for 19 degrees of freedom. (All confidence intervals quoted are 90% for one interesting parameter, with $\delta \chi^2 = 2.71$.) Here the galactic neutral hydrogen column density is held constant at the Stark et al. (1992) value of $3.4 \times 10^{20}$ cm$^{-2}$. This temperature determination is about 1 keV cooler than the M88 value of 3 keV. While M88 do not quote errors, typical uncertainties in IPC temperature determinations are 1.5 keV, so these values are marginally consistent. The M88 *Einstein* observations did not permit accurate estimation of the metallicity for comparison. The X-ray luminosity of this component is $8.7^{+9.7}_{-9.7} \times 10^{42} h_{75}^{-2}$ erg s$^{-1}$. Fitting a two-temperature model does not improve the value of $\chi^2$.

The secondary peak in the central X-ray emission has no obvious counterpart in the corresponding galaxy distribution, although the S0/E galaxy NGC6047 is located at its center. The best-fit model (with $\chi^2 = 14.21$ for 19 d.o.f.) is a thermal plasma with $T=1.03^{+0.60}_{-0.66}$ keV and metallicity of $0.32^{+0.15}_{-0.16}$ solar. Adding either a second temperature component or a power-law component does not reduce the value of $\chi^2$. Allowing the value of the galactic
absorption to be a free parameter does not change the fitted parameters significantly. The allowed range of the galactic column density brackets the measured value. Assuming that this feature is at the distance of A2151, the X-ray luminosity in the 0.1 - 2.0 keV band is $3.4^{+0.68}_{-0.61} \times 10^{42} h^{-2}_{75}$ erg s$^{-1}$. This luminosity is consistent with that of a poor cluster. Therefore we interpret the secondary peak as a cooler, relatively distinct component of the ICM. Unfortunately the M88 observation of A2151 did not permit a derivation of temperature for this peak.

The diffuse eastern component of X-ray emission contributes about 300 photons in our PSPC image, enough to attempt to fit a model spectrum. Once again we find that a single-temperature Raymond-Smith plasma provides the most consistent fit to the observed spectrum, with $T=0.85^{+0.21}_{-0.17}$ keV and $A=0.16^{+1.01}_{-0.13}$ solar. The value of $\chi^2$ for this model is 14.6 with 19 d.o.f. This feature has a luminosity of $5.2^{+3.7}_{-3.2} \times 10^{41} h^{-2}_{75}$ erg s$^{-1}$ in the 0.1 to 2.0 keV band of ROSAT, similar to that of a bright elliptical. However, there is no elliptical located at the centroid of this emission. Note that this temperature is significantly different from the temperature of the brightest peak.

Unlike the three brightest sources, the best-fit model for the northern X-ray peak is a power law, with photon index $2.44^{+0.18}_{-0.19}$. Allowing the neutral hydrogen column density to vary from the Stark et al. (1992) value yields a range from $2.1-5.6 \times 10^{20}$ cm$^{-2}$, which is consistent within the uncertainties. The $\chi^2$ for this model is quite good (24.3 for 23 d.o.f.): we tentatively identify the elliptical galaxy at this position, NGC6061, as an active galaxy. Assuming that the source has this power-law spectrum and is located at the distance of A2151, it has a luminosity of $1.6^{+0.20}_{-0.20} \times 10^{41} h^{-2}_{75}$ erg s$^{-1}$.

The X-ray properties of these sources are summarized in Table 1.

3. OPTICAL ANALYSIS
3.1 Quantifying the Substructure

Unlike the apparently more spherically-symmetric systems A1656 and A2256, no one has ever doubted the presence of substructure in the Hercules Cluster. Both Dressler & Shectman (1988) and West & Bothun (1990) find significant levels of substructure in A2151 using tests which combine velocity and position information. BDS use additional redshifts from optically-faint spirals, as well as the deep position catalog generated with the Minnesota Automated Plate Scanner (Dickey et al. 1987), to verify that the substructure is present in the faint galaxies as well as the bright ones. The kinematical properties of the complete cluster dataset are provided in Table 2.

We summarize the indicators of substructure for the restricted, 126 member BDS catalog in Table 3. The restricted dataset includes galaxies which lie within $3S_{BI}$ of the cluster velocity (where $S_{BI}$ is the robust estimator of dispersion described in Beers et al. 1990) and within $54'$ (or $2R_C$ as defined by Tarenghi et al. 1979). The diagnostics used 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 $\Delta$-, $\alpha$-, and $\epsilon$-statistics (Dressler & Shectman 1988; West & Bothun 1990; Bird 1993, 1994a respectively) use velocity and position information simultaneously to look for substructure. These tests are described in more detail in Bird (1993, 1994a) and references therein. 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 (the number reported in Table 3) 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 kurtosis and each of the three-dimensional statistics returns a positive detection. The value of the kurtosis (−0.563, where 0.000 is the rescaled Gaussian value) reveals that the velocity distribution is light-tailed compared to Gaussian. It has fewer members in the outer parts of the distribution than expected for a Gaussian of the same dispersion. This is often the case when a distribution is composed of two or more distinct subpopulations (Bird & Beers 1993; Ashman, Bird & Zepf 1994). The velocity separation between the BDS northern subcluster and the rest of the system is probably responsible for this result. (Note: BDS find that their unrestricted dataset, which includes 3 high-velocity galaxies which do not survive the $3S_BI$ filter, does not possess a significantly non-Gaussian kurtosis, although a more robust and conservative measure of tail population, the tail index TI (Bird & Beers 1993), is not consistent with Gaussian. Obviously the handling of outliers in the dataset can greatly influence the results of these tests, particularly tests which are classical, moment-based estimators.)

The three-dimensional diagnostics are all sensitive to local correlations between velocity and position. Their significant rejections all suggest the presence of kinematically-distinct subgroups in the A2151 dataset, which is unsurprising given its complex velocity structure and irregular galaxy distribution. Malumuth et al. (1992) and Bird (1994b) discuss the effects of smoothly-varying velocity fields and decreasing velocity-dispersion profiles on the 3-D estimators. Like A2107 (Oegerle & Hill 1992), the average velocity in A2151 varies relatively smoothly along its axis of elongation (see BDS Figure 8). Unlike A2107, however, the galaxy distribution in A2151 is extremely clumpy. Therefore it seems unlikely that smooth rotation explains the significant correlations between velocity and position in the Hercules Cluster.
To allocate the individual galaxies in the BDS dataset to their host subclusters, we have used the KMM mixture-modelling algorithm of McLachlan & Basford (1988). KMM is an implementation of a maximum-likelihood technique which assigns each galaxy into a prospective parent population, and evaluates the improvement in fitting a multiple-group model over a single-group model. This evaluation is based on the likelihood ratio test statistic or LRTS, which quantifies the probability that the given dataset is consistent with a single-group null hypothesis. KMM is applied to velocity and position data for 25 galaxy clusters in Bird (1994a).

One major difficulty in applying any objective partitioning algorithm without a priori knowledge of the system is the recognition and validation of the number of distinct groups present in the data. Using a “friends-of-friends” technique based on the Dressler-Shectman $\Delta$-statistic, BDS find statistical evidence for the existence of two groups, the central cluster and the northern subcluster. However, their technique cannot verify the existence of the third peak seen in the optical contour map. For convenience, and for comparison with the ROSAT image, we provide the BDS contour map superimposed on Dressler’s image of A2151 in Figure 2. This contour map was generated from the Automated Plate Scanner catalog of A2151 published by Dickey et al. (1987). Galaxies with magnitudes above 17.0 on the $E$-band Palomar Sky Survey plate (approximately equivalent to a red bandpass) are used to generate the map, to reduce contamination by background galaxies.

Buoyed by the discovery of hot gas in the same position as the eastern optical peak, and assuming that the kinematic evidence for the northern subgroup is convincing, we require KMM to fit three groups to the velocity and position data. (The negative detection of structure by the Lee statistic, in such an irregular system as A2151, also suggests that more than two groups are present in the position data.) Because the algorithm is so sensitive to
edge effects (i.e. the inclusion or exclusion of outliers can greatly affect the parameters of
the mixture model as noted above), we have restricted the analysis to galaxies meeting the
redshift cutoff defined above, and also lying within 33′ or about 1 Abell radius (∼ 1.5h⁻¹
Mpc) of the cluster centroid. This eliminates 15 galaxies from the fit; they are in the extreme
north and extreme south of the system. To verify that the substructure detected above is not
due to the presence of these outlying galaxies, we summarize the substructure diagnostics in
the radially-restricted dataset in the second line of Table 3. The kurtosis and the nearest-
neighbor diagnostics still reject their null hypotheses at a significant level, thereby showing
that the structure in A2151 is present even in the core of the system. The LRTS for this
subset is significant at a level of <0.001, providing us with statistical evidence that the three
groups seen in the optical contour map are physically distinct. That is, the KMM algorithm
rejects the single group hypothesis for the A2151 dataset at a confidence level of > 99.9%.

We have used the posterior probabilities assigned by the KMM algorithm to allocate each
galaxy in the (radially-restricted) dataset to its host subcluster. The kinematic properties
of the subsystems, coded A2151C, A2151N, and A2151E (for central, northern and eastern,
respectively) are compared to each other and to the global cluster properties in Table 3. The
position centroids are indicated by the letters C, N and E in Figure 2. Note that the use of
velocity information in the KMM partition has skewed the centroid of A2151E and A2151N
from the position dictated by the galaxy distribution alone. The coincidence between the
positions of the X-ray and optical peaks, for A2151C and A2151E, provides some verification
that KMM has allocated galaxies sensibly. (These positions are summarized in Table 4 and
discussed in further detail in the next section.) In Figure 3 we present the velocity histograms
for the three subclusters.

We check the partition more closely by looking for additional indications of substruc-
ture within the subclusters themselves. This is somewhat risky because they contain so few galaxies, but the resampling technique used for determining significance levels for all the substructure tests accurately estimates the uncertainty in the test statistic due to Poisson fluctuations, even in small datasets. Unlike the complete dataset or the radially-restricted subset, for which several of the substructure diagnostics were positive, only A2151C shows any indication of substructure. The central subcluster has a significant Δ-statistic although none of the other tests are positive. A2151N and A2151E possess no detectable substructure. This result suggests that KMM has divided the cluster into reasonable, if not unique subsystems.

3.2 Kinematical and Morphological Properties of the A2151 Subclusters

We have supplemented the kinematical and dynamical information with the individual galaxy morphological types taken from Dressler (1980). Many authors have noted that a cluster’s spiral fraction is anticorrelated with the presence of hot intracluster gas (Bahcall 1977; M88; Arnaud et al. 1992). The spiral fractions (not including S0’s) for the 3 subclusters are A2151C: 49% (30 out of 61); A2151N: 63% (20 out of 32); A2151E: 53% (8 out of 15). In each of the subclusters one galaxy was not included in the Dressler catalog and has therefore been removed from further morphological analysis. The spiral fractions are all consistent within the sampling errors despite the differences in gas properties in the three subsystems. High-resolution VLA 21-cm maps of spirals in A2151 (Dickey 1995) reveal that the spirals in A2151C and A2151E are considerably deficient in neutral hydrogen compared to spirals in the north. This is presumably related to the lack of intracluster gas in the north, either as an agent of ram-pressure stripping or as a repository for the missing gas.

Even when the substructure is considered, however, kinematical differences between the spirals, ellipticals and S0’s exist. These properties of the morphological subsets are presented
in Table 5. In A2151C the spirals have a higher average velocity (defined using the robust estimator $C_{BI}$; Beers, Flynn & Gebhardt 1990) than the ellipticals. In A2151N the offset exists but is only marginally significant. (We have not considered A2151E in this discussion because it contains only 2 ellipticals.) In A2151N the two subsets have similar velocity scales (the velocity dispersion or scale is defined using the robust estimator $S_{BI}$). In A2151C, however, the three subsets are quite different. The velocity locations of the spirals is much different from that of the earlier types. This may be an indication of spiral infall, especially since their velocity location is higher than that of the ellipticals and S0’s (that is, it is more similar to the velocity of A2151N which may be a source of galaxies). More difficult to understand, however, is the fact that the velocity dispersion for the S0 galaxies is much higher than that of either the ellipticals or spirals. This effect is only evident when the cluster’s structure is considered, so it was not obvious in the Zabludoff & Franx (1993) results. They do find a similar situation in DC2048-52, a cluster with smoother galaxy distribution than A2151 but with strong evidence for substructure from the nearest-neighbor diagnostics (Bird 1993).

4. SUMMARY AND INTERPRETATION

We combine our conclusions about the X-ray and optical substructure in the Hercules Cluster to suggest a consistent model of this cluster’s dynamical state.

1) Our PSPC image reveals that the BDS northern subcluster has no detectable diffuse X-ray emission. The eastern peak in the galaxy distribution which BDS could not verify does coincide with an enhancement above the X-ray background, suggesting that it is physically distinct. The bimodality that M88 detected in the central cluster emission does not correspond to any feature in the galaxy distribution in the same area.
2) Analysis of the X-ray spectra reveal a difference in temperature between A2151C and A2151E. A2151E is significantly cooler than the brightest peak of emission (0.85 keV vs. 1.67 keV), although it is marginally consistent with the second central peak. The complexity in the X-ray structure, both spatial and temperature, implies that the ICM in the Hercules Cluster is far from its equilibrium state.

3) A maximum-likelihood analysis of the BDS galaxy velocities and positions, constrained to fit three subclusters, reveals significant kinematic differences between A2151C, A2151N and A2151E. A2151N is higher in line-of-sight velocity than either of its companion systems. The subset of S0 galaxies in A2151C has a much higher velocity scale than either the spirals or ellipticals. The velocity dispersion of A2151E is consistent (with the 90% confidence intervals) with that of A2151C, although its ICM is significantly cooler.

The low temperatures of the diffuse cluster emission move A2151 even farther away from the $\sigma_v - T_x$ relationship found by Edge & Stewart (1991) (see also Bird & Mushotzky 1994) than Einstein results suggested. This relation, derived from virial considerations, relates the properties of the galaxies to those of the gas:

$$T_x = 6.026 \times 10^{-4}\sigma_v^{1.35}$$

where $T_x$ is in units of keV and $\sigma_v$ is in units of km s$^{-1}$. Equation (1) predicts that A2151C should have an X-ray temperature of 4.2 keV, far warmer than the PSPC value. A2151E is predicted to be at 3.2 keV, much hotter than the 0.8 keV gas we detect in the PSPC image. Similarly, A2151N, which has no detectable emission, is predicted to have a temperature of 2.3 keV. We take this disagreement as evidence of a recent merger event in A2151, which has disrupted the (assumed) hydrostatic equilibrium of the ICM within the subclusters. The presence of substructure in both the galaxy and gas distributions is clear in A2151. If the cluster is pre-merger, the subclusters should themselves be virialized and unperturbed in
most hierarchical formation models (as is the case in the well-known bimodal system A548; Davis et al. 1994). Even within the subclusters, however, the virial condition defined above is violated. We suggest that this is because the subclusters have been violently disrupted by their interaction.

Because even within the subclusters the galaxies and gas are out of equilibrium with each other, mass estimation based on either galaxy or gas dynamics (for which an equilibrium situation must be assumed) is highly inaccurate. For this reason we have not derived either an X-ray or an optical mass for any of the A2151 subclusters.

Burns et al. (1994, hereafter B94) find evidence using ROSAT images of clusters that radio galaxies, especially wide-angle tail sources (WATs), are preferentially located within clumps of X-ray gas. They interpret the existence of the WAT as evidence of extreme turbulence in the ICM, i.e. as yet another indication of a recent merger event. Specific examples of this phenomenon can be seen in A400 (Beers et al. 1990) and A2634 (Pinkney et al. 1993), which both have extremely radio-loud central galaxies. To test this hypothesis for A2151, we have used the catalog of Zhao et al. (1989) to look for WAT galaxies in A2151. In Table 4, the results of this search are compared to the X-ray and optical peaks from the present study. A2151E does not contain an identified radio source, but both of the central peaks as well as the northern active galaxy do coincide with radio galaxies. NGC 6040, located at the brightest X-ray peak, is a narrow angle tail galaxy. Both NGC 6047, which coincides with the secondary central peak, and the previously-mentioned NGC 6061 (see Sect. 2) are WAT sources. The lack of detectable gas in A2151N provides some difficulty for a recent merger as a trigger of WAT activity in NGC 6061, but is consistent with the 25% of sources found by B94 which are not correlated with any obvious X-ray emission.

Computer simulations of subcluster mergers also presented by B94 lend further weight
to the post-merger interpretation of A2151C and A2151E. Their code, described in detail in Roettinger, Burns & Loken (1993), includes N-body and hydrodynamical algorithms to follow evolution of dark matter, galaxies and gas, as well as both bremsstrahlung and line-emission cooling. They find that the less-massive subcluster is ram-pressure stripped of most of its gas, and that the remaining gas is cooler, similar to the observed situation in A2151C and A2151E. In this interpretation, the secondary X-ray emission centered on NGC 6047 is the ram-pressure stripped gas from A2151E, trapped within the presumably deeper gravitational potential of A2151C.

Determining whether any particular cluster is pre- or post-merger is an extremely difficult (if not impossible) task, and we would therefore like to stress that our assessment of A2151 as a post-merger system is tentative. Nonetheless, we believe that the following observations lend support to this interpretation. The deviation of the A2151 subclusters (A2151C and A2151E) from the virial relationship between galaxy velocity dispersion and X-ray temperature suggests that some disruptive physical event must have already occurred. If the subclusters had not interacted, one might expect that their gas and galaxies would be in agreement with the $\sigma_v - T_x$ relationship, as is the case in A548 (Davis et al. 1994). (Alternatively, it is possible that A2151C and A2151E are themselves in the process of formation.) Similarly, B94 argues that the presence of WAT radio sources in clusters is a signal that subcluster mergers have recently occurred. The radio activity of NGC 6040 and NGC 6047 may therefore indicate that A2151C has just undergone a merger event.

We interpret the lack of X-ray gas corresponding to the optical galaxy enhancement A2151N to mean that those galaxies are not themselves a physically-distinct subgroup, but are instead galaxies infalling from the Hercules Supercluster. In general, spiral infall is detected in clusters when late-type galaxies are preferentially located in the outer parts of
the cluster, and when they possess a much larger velocity dispersion than early-type galaxies (cf. Virgo, Tully & Shaya 1984; A2634, Scodégio et al. 1994). Such an enhanced velocity dispersion is not seen in any of the A2151 subclusters. Nonetheless, because A2151N lies within the Hercules Supercluster, it is possible that its velocity dispersion is lower than might be expected for a system embedded within a less structured environment.

The combination of imaging and spectroscopy in X-ray, optical and radio wavelengths, as well as physically realistic computer simulations, provides us with a possible understanding of A2151, the Hercules Cluster. In this complex system, we find evidence for a recent merger event as well as galaxy infall into the cluster core. Each of the observational and computational components provides an important part of the dynamical analysis of this cluster of galaxies. The value of a multiwavelength approach to galaxy clusters can hardly be over-emphasized.

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REFERENCES

Arnaud, M., Rothenlug, R., Boulade, O., Vigroux, L & Vangioni-Flam, E. 1992, A&A, 254, 49

Ashman, K.M., Bird, C.M. & Zepf, S.E. 1994, AJ, submitted

Bahcall, N.A. 1977, ApJL, 218, L93

Baier, F.W. 1983, Astron. Nach., 5, 211

Beers, T.C., Forman, W., Huchra, J.P., Jones, C. & Gebhardt, K. 1991, AJ, 102, 1581

Beers, T.C., Flynn, K. & Gebhardt, K. 1990, AJ, 100, 32

Bird, C.M. 1993, Ph.D thesis, University of Minnesota and Michigan State University

Bird, C.M. 1994a, AJ, 107, 1637

Bird, C.M. 1994b, ApJ, 422, 480

Bird, C.M. & Beers, T.C. 1993, AJ, 105, 1596

Bird, C.M., Dickey, J.M. & Salpeter, E.E. 1993, ApJ, 404, 81 (BDS)

Bird, C.M. & Mushotzky, R.F. 1994, ApJ, submitted

Burns, J.O., Rhee, G., Owen, F.N. & Pinkney, J. 1994, ApJ, to appear 1 March

Burns, J.O., Roettiger, K., Pinkney, J., Loken, C., Doe, S., Owen, F., Voges, W. & White, R. 1994, to appear in the Proceedings of the ROSAT Science Symposium (B94)

David, L.P., Slyz, A., Jones, C., Forman, W., Vrtilek, S.D. & Arnaud, K.A. 1993, ApJ, 412, 479

Davis, D. S. & Mushotzky, R. F. 1993, AJ, 105, 491

Davis, D. S., Bird, C. M., Mushotzky, R. F. & Odewahn, S. C. 1993, ApJ submitted

Dickey, J.M., Keller, D.T., Pennington, R. & Salpeter, E.E. 1987, AJ, 93, 788

Dressler, A. 1980. ApJS, 42, 565

Dressler, A. & Shectman, S. 1988, AJ, 95, 985

19
Edge, A.C. & Stewart, G.C. 1991, MNRAS, 252, 428
Fitchett, M.J. 1988, MNRAS, 230, 169
Fitchett, M. & Merritt, D. 1988, ApJ, 335, 18
Forman, W., Bechtold, J., Blair, R., Giacconi, R., Van Speybroeck, L., & Jones, C. 1981, ApJLett, 243, L133
Geller, M.J. & Beers, T.C. 1982, PASP, 94, 421
Henry, J.P., Henriksen, M., Charles, P., & Thorstensin, J. 1981, ApJL, 243, L137
Jones, C. & Forman, W. 1992, in Clusters and Superclusters of Galaxies, ed. A.C. Fabian, (Dordrecht: Kluwer), 49
Kent, S.M. & Gunn, J.E. 1982, AJ, 87, 945
Kent, S.M. & Sargent, W.L.W. 1983, AJ, 88, 697
Magri, C., Haynes, M., Forman, W., Jones, C., & Giovanelli, R. 1988, ApJ, 333, 136 (M88)
Malumuth, E.M., Kriss, G.A., Van Dyke Dixon, W., Ferguson, H.C. & Ritchie, C. 1992, AJ, 104, 495
McLachlan, G.J. & Basford, K.E. 1988, Mixture Models, (New York: Marcel Dekker)
Mohr, J., Fabricant, D. & Geller, M. 1993, CfA preprint
Mushotzky, R.F. 1984, Physica Scripta, T7, 157
Roettinger, K., Burns, J. & Loken, C. 1993, ApJ, 407, L53
Scodeggio, M., Solanes, J.M., Giovanelli, R. & Haynes, M.P. 1994, Cornell preprint
Snowden, S. L., McCammon, D., Burrows, D. N. & Mendenhall, J. A. 1993 ApJ, submitted
Stark, A.A., Gammie, C.F., Wilson, R.W., Bally, J., Linke, R.A., Heiles, C.M. & Hurwitz, M. 1992, ApJSuppl, 79, 77
Tarenghi, M., Tifft, W.G., Chincarini, G., Rood, H.J. & Thompson, L.A. 1979, ApJ, 234, 793
Tully, R.B. & Shaya, E. 1984, ApJ, 281, 31
Veron-Cetty, M.-P. & Veron, P. 1987, ESO Scientific Report #5
West, M.J. & Bothun, G.D. 1990, ApJ, 350, 36
White, S.D.M. 1992, in *Clusters and Superclusters of Galaxies*, ed. A.C. Fabian, (Dordrecht: Kluwer), 17
White, S.D.M., Briel, U.G. & Henry, J.P. 1993, MNRAS, 261, L8
Zabludoff, A.I. & Franx, M. 1993, AJ, 106, 1314
Zhao, J-H., Burns, J.O. & Owen, F.N. 1989, AJ, 98, 64
TABLE 1. X-ray Properties of Bright Sources in PSPC Image.

| Source   | Extraction Flux | $L_{0.1-2.0}$ | $kT$ | $A$   | $\chi^2/\nu$ |
|----------|----------------|---------------|------|-------|--------------|
|          | Radius (kpc)   | (10^{-12} ergs s^{-1} cm^{-2}) | (10^{42} h^{-2} ergs s^{-1}) | (keV) | (solar units) |               |
| A2151C (bright) | 210 | 3.1$^{+0.26}_{-0.26}$ | 8.7$^{+9.7}_{-9.7}$ | 1.67$^{+0.47}_{-0.25}$ | 0.56$^{+0.31}_{-0.20}$ | 24.92/19 |
| A2151C (faint)   | 200 | 1.3$^{+0.24}_{-0.22}$ | 3.6$^{+0.68}_{-0.68}$ | 1.03$^{+0.60}_{-0.06}$ | 0.32$^{+0.15}_{-0.10}$ | 14.21/19 |
| A2151E           | 130 | 1.9$^{+1.33}_{-1.81}$ | 0.050$^{+0.37}_{-0.32}$ | 0.85$^{+0.21}_{-0.17}$ | 0.16$^{+1.01}_{-0.13}$ | 14.6/19  |
| A2151N          | 151 | < 1.2 $\times$ 10^{-14} | $\alpha$ | $\alpha$ | $\alpha$ | $\alpha$ |
| NGC 6061        | 151 | 0.57$^{+0.07}_{-0.07}$ | 1.6$^{+0.20}_{-0.20}$ | 2.44$^{+0.18}_{-0.19}$ | 24.3/23  |

Notes to TABLE 1. The positions of the ROSAT sources are provided in TABLE 4 for easier comparison with their optical and radio counterparts.

For all spectral models, the galactic hydrogen abundance was held constant at the Stark et al. (1992) value of $3.4 \times 10^{20}$ cm^{-2}. See text for further discussion.
### TABLE 2. Dynamical Properties of A2151 and Subclusters.

| System | $\alpha$ (J2000.0) | $C_{BI}$ (km s$^{-1}$) | $S_{BI}$ (km s$^{-1}$) |
|--------|---------------------|------------------------|------------------------|
|        | $\delta$ (J2000.0) | $IC_{BI}$ (90%)        | $IS_{BI}$ (90%)        |
| A2151  | 16:05:37.2          | 11066                  | 752                    |
|        | 17:49:08.4          | (–121, 116)            | (684, 826)             |
| A2151' | 16:05:25.9          | 11070                  | 766                    |
|        | 17:47:50.3          | (–131, 115)            | (696, 852)             |
| A2151C | 16:05:15.5          | 10650                  | 707                    |
|        | 17:39:45            | (–153, 152)            | (623, 820)             |
| A2151N | 16:05:55.0          | 11445                  | 455                    |
|        | 18:08:27            | (–123, 138)            | (384, 549)             |
| A2151E | 16:06:44.2          | 11756                  | 570                    |
|        | 17:46:13            | (–247, 437)            | (412, 820)             |

Note to TABLE 2. A2151' designates the radially-restricted dataset used in the KMM partition.
### TABLE 3. Substructure Diagnostics for A2151 and Subclusters.

| System | Skewness | Kurtosis | Lee  | $\Delta$ | $\alpha$ | $\epsilon$ |
|--------|----------|----------|------|----------|----------|-----------|
| A2151  | 0.242    | 0.061    | 0.134| <0.001   | 0.012    | <0.001    |
| A2151' | 0.216    | 0.072    | 0.558| <0.001   | 0.034    | <0.001    |
| A2151C | 0.160    | 0.344    | 0.120| 0.002    | 0.128    | 0.168     |
| A2151N | 0.355    | 0.338    | 0.736| 0.364    | 0.182    | 0.388     |
| A2151S | 0.160    | 0.344    | 0.946| 0.142    | 0.502    | 0.584     |

Note to TABLE 3. We have quoted significance levels for each of the substructure diagnostics. By convention, substructure is detected if this number is less than 0.100.
### TABLE 4. X-ray, Radio and Optical Correspondences

|          | ROSAT peak | Radio Source | Optical ID |
|----------|------------|--------------|------------|
| A2151C   |            |              |            |
| α(J2000.0) | 16:04:33.9 | 16:04:26.4   | NGC 6040† |
| δ(J2000.0) | 17:43:13.6 | 17:44:30.6   |            |
| α(J2000.0) | 16:05:07.5 | 16:05:09.0   | NGC 6047† |
| δ(J2000.0) | 17:43:43.9 | 17:43:47.4   |            |
| A2151E    |            |              |            |
| α(J2000.0) | 16:06:33.6 | no radio     | 16:06:44.3† |
| δ(J2000.0) | 17:43:58.3 | counterpart   | 17:46:12.6 |
| A2151N    |            |              |            |
| α(J2000.0) | no diffuse | no central   | 16:05:55.0 |
| δ(J2000.0) | X-ray component | radio source | 18:08:27.1 |
| α(J2000.0) | 16:06:14.9 | 16:06:16.3   | NGC 6061   |
| δ(J2000.0) | 18:15:13.6 | 18:14:59.5   |            |

† Both NGC 6040 and NGC 6047 are within the 1σ position centroids of A2151C.
†† The positions listed for A2151E and A2151N are taken from the KMM partitions.
| Subset (N_{gal}) | A2151C | A2151N |
|-----------------|-------|-------|
| Ellipticals (10)| 10172 (−226, 230) | 11305 (−234, 217) |
| S0’s (19)       | 10547 (−404, 395) | 11568 (−244, 119) |
| Spirals (27)    | 10793 (−189, 195) | 573 (448, 764) |
| E+S0’s (12)     | 404 (294, 556)    | 453 (323, 632) |
| Spirals (19)    | 882 (732, 1127)   | 455 (324, 565) |
FIGURE CAPTIONS

Figure 1. The ROSAT PSPC image of A2151.
Figure 2. Dressler’s Schmidt image of A2151 (Dressler 1980). The overlaid contour map is taken from BDS. The contours are linearly spaced in units of 0.0257 galaxies arcmin$^{-2}$ and range from 0.0015 to 0.2582 galaxies arcmin$^{-2}$ from lowest to highest. The letters C, N and E indicate the position centroids of the groups identified by KMM (see Section 3.1 for discussion).
Figure 3. Velocity histograms for A2151C (top panel), A2151N (middle panel), and A2151E (bottom panel).