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Using Intracluster Light to Study Cluster Evolution

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Abstract
We present some early results from our deep imaging survey of galaxy clusters intended to detect and study intracluster light (ICL). From our observations to date, we find that ICL is common in galaxy clusters, and that substructure in the ICL also appears to be common as well. We also discuss some initial comparisons of our imaging results to high-resolution numerical simulations of galaxy clusters, and give avenues for future research.

1.1 Introduction

The concept of intracluster starlight (ICL), or stars between the galaxies in galaxy clusters is not a new one: it was first proposed over 50 years ago (Zwicky 1951). However, progress in studying ICL has been slow due to its low surface brightness, which is less than 1% of the brightness of the night sky (see Vílchez-Gómez 1999, Feldmeier 2000 for reviews). This is unfortunate, because ICL is a powerful probe of the evolution of galaxies in clusters (Dressler 1984), and of cluster evolution overall.

In the last six years however, the study of ICL has increased dramatically. Numerous individual intracluster stars have been detected in nearby and distant galaxy clusters (Arnaboldi et al. 1996; Theuns & Warren 1997; Feldmeier, Ciardullo & Jacoby 1998; Ferguson, Tanvir & von Hippel 1998; Durrell et al. 2002; Feldmeier et al. 2003; Arnaboldi et al. 2003; Gal-Yam et al. 2003). At the same time, deep imaging of clusters with CCD detectors have also detected the intracluster light (Uson, Boughn, & Kuhn 1991; Víchez-Gomez, Pelló, & Sanahuja, 1994; Bernstein et al. 1995; Gonzalez et al. 2000). Detections of tidal debris arcs (Trentham & Mobasher 1998; Gregg & West 1998; Calcañeo-Roldán et al. 2000) in clusters have shown that at there is significant substructure in the ICL, and that the production of ICL is ongoing.

Encouraged by these results, we have undertaken a deep imaging survey of galaxy clusters, intended to quantify the properties of ICL as a function of environment, and overall galaxy cluster properties. From our deep imaging, with careful attention to systematic errors (e.g., Morrison, Boroson, & Harding 1994; Morrison et al. 1997), we are able to measure the ICL to faint surface brightnesses many magnitudes below that of the night sky ($\mu_{\mathrm{V,ICL}}$ $\approx$ 26–28). In tandem with the observations, we are constructing numerical simulations of galaxy clusters in a cosmological context, similar to those of Dubinski (1998).

Here, we present the results of our deep imaging survey to date. We note that there are

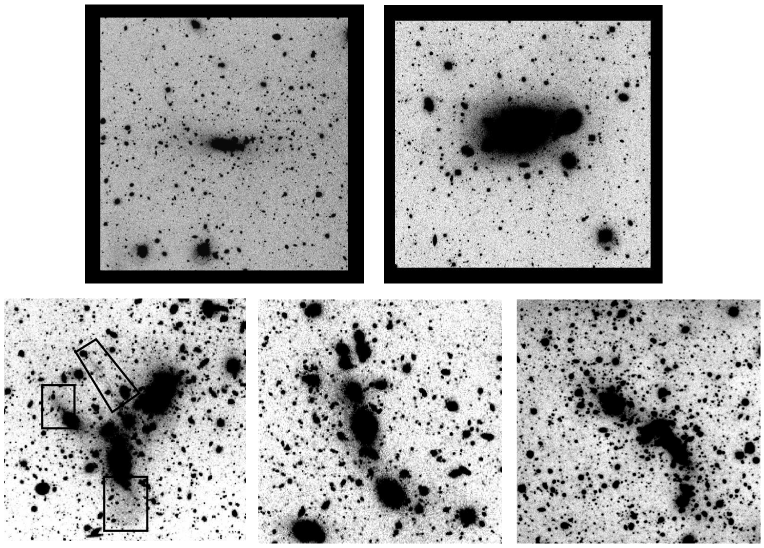

Fig. 1.1. Images of five clusters observed in this survey. From left to right and top to bottom, they are: Abell 1413, MKW 7, Abell 1914, Abell 1234, and Abell 1553. The last three clusters show only the central section of the image; these clusters show a wealth of ICL substructure. Many of the brighter galaxies at the center of each cluster lie within a low surface brightness common envelope, and there are clearly defined tidal features, most noticeably in Abell 1914 (denoted by the boxes). This in contrast to the first two clusters, which had less substructure (Feldmeier et al. 2002).

several other searches for ICL underway that have complementary goals (see Gonzalez et al. this volume; Krick et al. this volume).

1.2 The Survey

For our initial survey, we focus on observing Abell clusters (Abell, Corwin, & Olowin 1989) at large distance classes (5–6, corresponding to z $\approx$ 0.1–0.2). This is to ensure that the entire cluster is contained in our field-of-view for good sky subtraction, but the clusters are not so distant that cosmological $(1+z)^4$ surface brightness dimming is a major effect. We are also observing a few nearby clusters from the MKW/AWM (Morgan, Kayser, White 1975, Albert, White, & Morgan 1977) as a comparison sample. Our goal is to gather a *representative* sample of clusters with different richness, Bautz-Morgan and Rood-Sastry types. We have observed ten clusters so far (ACO 84, 98, 545, 801, 1234, 1413, 1553, 1914, 2443 and MKW 7), and plan to observe 4–5 more before completing this initial survey.

We observe using the KPNO 2.1m, and image through the Washington *M* filter, which is similar to *V* but contains fewer night sky emission lines. We use the ultra-deep surface photometry techniques of Morrison, Boroson, & Harding (1994) for our observations and data reduction. We spend half of our telescope time constructing our dark sky flats (which are flat to 0.3% on all scales in the worst case), and the other half observing the clusters. We then carefully mask out all objects in our frames, using a combination of the DAOPHOT (Stetson 1987), SExtractor (Bertin & Arnouts 1996) and our own software. After detecting

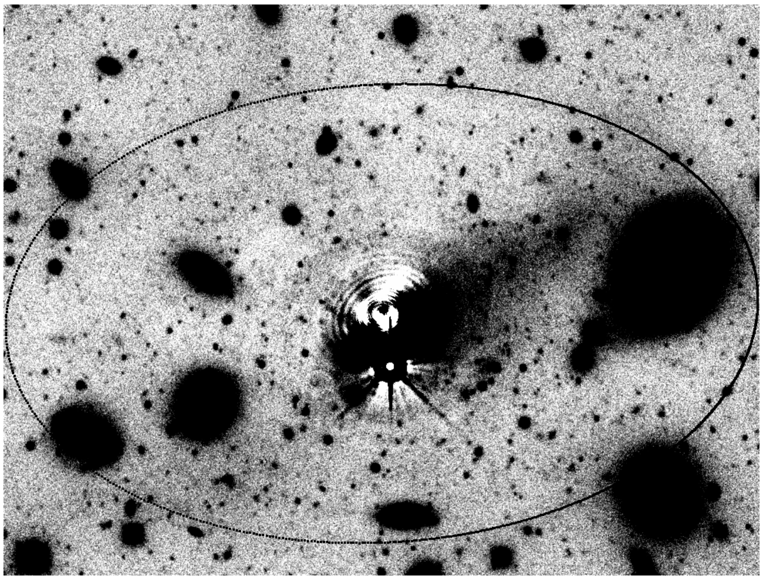

Fig. 1.2. Our residual image for MKW 7, after the best-fitting elliptical model of the cD + ICL has been subtracted. The black ellipse shows where the measured surface brightness has a signal-to-noise greater than five. A large tidal plume is apparent leading from the center of the image to the right (south), and up (west) of the galaxy's nucleus. The magnitude of this plume is approximately equal to a small galaxy ($M_{\rm V} \sim -17$)

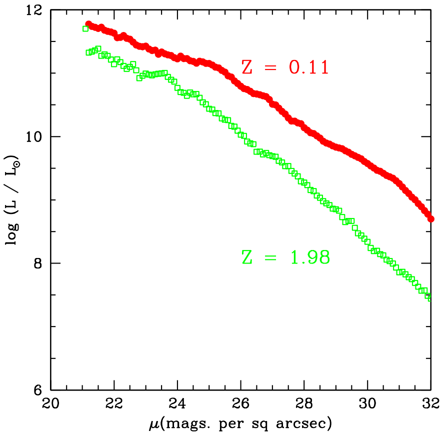

Fig. 1.3. A surface brightness histogram of all starlight from a N-body simulation by Dubinski (1998). As can be clearly seen, as the cluster evolves, more starlight is accreted (causing an offset between the two histograms), and starlight is stripped from the high-surface brightness galaxies, and re-distributed into lower surface brightness ICL features. This stripping causes the surface brightness histogram slope to become more shallow over time. This relation, which is in principle observable, may allow us to place limits on the dynamical age of galaxy clusters.

the ICL, we construct an error model for each cluster that includes all sources of error, both random and systematic. Our data has a signal-to-noise of five (including systematic errors; see Feldmeier et al. 2002 for an example of the error model) at a surface brightness of 26.5 mag arcsec^{-2}. The signal-to-noise ratio approaches unity at μ_V= 28.3 mag arsec^{-2}.

The results of the first two clusters have been published in Feldmeier et al. (2002): work is ongoing on the other clusters. A mosaic of the first five clusters is shown in Figure 1.1. Once this initial survey is complete, we plan to observe nearby clusters using the CWRU Burrell Schmidt, which is currently being optimized for ultra-deep surface photometry.

1.3 Results

From the clusters we have observed so far, it seems that diffuse intracluster light and intracluster tidal debris is common in galaxy clusters. Fig 1.2 shows an example of a tidal plume superimposed over the brightest cluster galaxy in the cluster MKW 7. Similar tidal features can be seen in Abell 1914 (see the boxed regions in Figure 1.1), and in several other clusters. Although our sample is still small, it seems that the clusters that are cD-dominated (Abell 1413, MKW 7) have smoother, more regular ICL than those in clusters that do not have a cD galaxy (ACO 1234, 1553 & 1914). In these non cD clusters, the ICL follows an irregular distribution, and is not well correlated with galaxy density.

Tidal features of the kind we have detected can be seen in high-resolution cluster N-body simulations (e.g., Moore et al. 1996; Dubinski 1998; Dubinski, Murali, & Ouyed 2001; see also Willman, this volume), but thus far we have seen few long tidal debris arcs. Plume-like intracluster debris structures seem to be more common in the clusters we have surveyed thus far. However, it is clear from the simulations that the vast majority of tidal debris seen in cluster simulations has a surface brightness much lower than our limit of μ_V= 26.5 mag arsec^{-2} for the initial observations. The structures that we have observed are likely to be the brightest features in each cluster.

Another interesting facet of our observations is the nature of cD galaxy envelopes, which are characterized by an excess of diffuse light (compared to an $R^{1/4}$ law) at large radius. The origin of cD envelopes remains unclear: are they formed in the initial stages of cluster collapse (Merritt 1983, 1984), or later, as galaxies continue to fall in the cluster and become tidally stripped? The accepted view of cD envelopes (Schombert 1992) is that cDs in rich galaxy clusters have large extended cD envelopes, while brightest cluster galaxies in poorer clusters do not. In our observations of Abell 1413 and MKW 7, we have found the opposite behavior: MKW 7, a poor cluster has a strong cD envelope, while Abell 1413 has a weaker cD envelope than previously measured. Since other researchers have also found cDs in rich clusters with pure $R^{1/4}$ laws (e.g., Gonzalez 2000), this may signify that the earlier photographic surface photometry of cDs may need to be re-examined.

1.4 Future Work

Our initial survey will be completed by the end of 2003: we then plan to begin observations on the Burrell Schmidt. The wide field of view of the Schmidt ($\approx$ 1.5 degrees) will allow us to observe more nearby galaxy clusters, where much more is known about their properties. We also plan to run additional large-scale galaxy cluster simulations over a range of cosmologies and initial conditions so that we can make detailed comparisons between our imaging survey and theoretical results.

A final goal is to create quantitative metrics for the ICL that can be used on simulations and observations. In Figure 1.3 we show one potential metric: the amount of stellar luminosity as a function of surface brightness, applied to the cluster simulation of Dubinski (1998) at two different redshifts. In this relation, dynamically evolved clusters have a shallower slope to their "surface brightness distribution function" than dynamically younger clusters. From comparison of multiple simulations, the intrinsic scatter in this slope at fixed redshift is low ($\approx 4\%$). More testing is needed, but the results seem promising.

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