NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: April 1, 2002 **Category:** Clusters of Galaxies

Observing the formation of cD envelopes and intracluster light

PI: John Feldmeier **Status:** P **Affil.:** Case Western Reserve University
Department of Astronomy, 10900 Euclid Ave, Cleveland, OH 44106 USA
Email: johnf@eor.astr.cwru.edu Phone: 216-368-0310 FAX: 216-368-5406

CoI: Chris Mihos **Status:** P **Affil.:** Case Western Reserve University
CoI: Heather Morrison **Status:** P **Affil.:** Case Western Reserve University
CoI: Paul Harding **Status:** P **Affil.:** Case Western Reserve University

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)***:**

We propose deep imaging to continue our study of the intracluster light (ICL) and extended halos of cD galaxies in galaxy clusters as a function of cluster environment. The ICL is likely formed both from violent relaxation during cluster formation and from subsequent tidal stripping of cluster galaxies, so that its properties should be linked to the dynamical evolution of the cluster and may vary between clusters with different physical properties. Our most recent imaging data seem to reflect such a trend: the observed morphology of the ICL varies significantly as a function of cluster Bautz-Morgan type. To the extent that the Bautz-Morgan type reflects cluster dynamical state, this result implies that we are beginning to see how ICL is formed and how it evolves with time.

While our preliminary results are exciting, they are based on a small number of clusters. To extend and confirm our results, we propose to target six rich Abell clusters which span a range of Bautz-Morgan type, focusing this time on cD-dominated type I and intermediate type II clusters. In addition, we also plan to observe several MKW/AWM poor clusters to see how the properties of ICL vary as a function of cluster richness. This sample will allows us to probe how the properties of the ICL and cD halos vary over a range of cluster environments. We are requesting 7 dark nights on the 2.1m to reach $\mu_V = 26.5$ mag/sq arcsec in each cluster.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Moon	Optimal months	Accept. months
1	KP-2.1m	CFIM + T2KA	7	darkest	Sep - Jan	Sep - Jan
2						
3						
4						
5						
6						

Scheduling constraints and non-usable dates *(up to four lines)*.

Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

The study of intracluster light (ICL) in galaxy clusters has been of great interest ever since Zwicky (1951) first claimed the detection of stars in between the galaxies of Coma. The reason for this interest is clear: the dynamical evolution of cluster galaxies is complex, and involves the poorly understood processes of galactic encounters, dark matter, cluster accretion, and tidal stripping (cf. Dressler 1984). The ICL provides a direct way to study these different mechanisms. Depending on the dynamical state of the cluster environment, the ICL could contain anywhere between 10% and 70% of the cluster's total luminosity (e.g., Richstone & Malumuth 1983). More recent studies of individual intracluster stars in the Virgo cluster (e.g., Ferguson *et al.* 1998; Feldmeier *et al.* 1998; Feldmeier *et al.* 2002) also suggest that the amount of ICL is large (at least $\sim 20\%$ of the total cluster starlight). However, although the presence of intracluster stars has been demonstrated, there is little information on how the amount and distribution of ICL varies with the properties of the cluster it inhabits.

To address these concerns, we have recently begun deep imaging of clusters in order to quantify the spatial distribution and amount of ICL as a function of cluster environment, as well as to search for substructure within the ICL. On our first 2.1m observing run we obtained high-quality deep surface photometry for two galaxy clusters (Feldmeier *et al.* 2002), and we have just obtained good data on at least two more (Figure 1). These data point towards an exciting new result: the morphology of the ICL appears correlated with cluster morphology. Clusters of Bautz-Morgan type I (cD-dominated) are characterized by smooth $r^{\frac{1}{4}}$ ICL surface brightness distributions extending over a large physical extent, and show very little large-scale substructure. In contrast, type III clusters (which contain several comparably luminous bright galaxies) show a much more complicated ICL structure – we see evidence for a common envelope of ICL surrounding the luminous galaxies, as well as significant substructure in the form of large scale plumes and thin tidal streams. As Bautz-Morgan type likely reflects cluster evolution, the difference in ICL properties may reflect how the ICL is formed and evolves with time. In evolved, cD-dominated Type I clusters, the ICL may have formed early during initial cluster collapse and has since relaxed into a smooth $r^{\frac{1}{4}}$ distribution, while Type III clusters may be much less evolved and possess an ICL which has not yet fully mixed and shows more substructure.

While intriguing, our results are based on a small number of clusters. Furthermore, one of our two Type I clusters is exceptionally rich (Abell 1413), while the other Type I is a small MKW cluster. More clusters are needed to confirm and extend our results, particularly clusters of Type I and II. Therefore, we propose to continue our search for the ICL in other rich Abell clusters, focusing this time on the cD-dominated and intermediate Type I and II clusters. Further observations will permit us to test more robustly this suggested trend of ICL morphology with cluster type, as well as allowing us to explore the variety of ICL morphology within a given cluster type.

Another important aspect of ICL substructure is tidal debris arcs, long arc-like structures caused by tidal stripping of galaxies as they move through the cluster. Such arcs have recently been found in the Coma and Centaurus clusters (Trentham & Mobasher 1998; Gregg & West 1998; Calcáneo-Roldán *et al.* 2000), at surface brightnesses readily obtainable with our proposed observations. Since tidal stripping occurs most efficiently in rich virialized clusters where galaxy halos are tidally truncated, these arcs may be much rarer in poorer and/or less evolved clusters. From our observations, we will be able to place limits on the frequency and properties of these arcs (see Figure 2) in a well-defined sample of galaxy clusters with differing richness. In conjunction with our ongoing dynamical modeling of cluster galaxies, these observations will constrain the processes which drive the formation and evolution of intracluster light and cD galaxy halos.

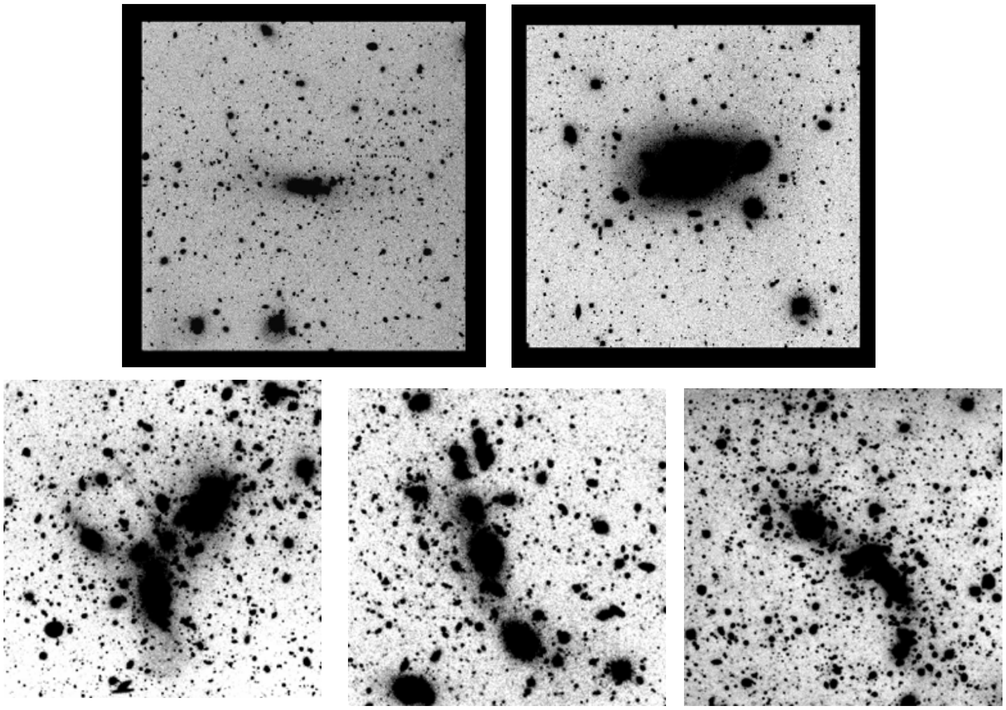

Figure 1: Images of all five clusters observed thus far in this survey. From left to right and top to bottom, they are: Abell 1413, MKW 7, Abell 1914, Abell 1234, and Abell 1553. The last three clusters were taken three weeks ago, and show only the central section of the image; these clusters show a 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. This in contrast to the first two clusters, which had less substructure (Feldmeier *et al.* 2002). (Due to the problems converting FITS images to postscript, the limitations of printers, and the invariable chain of photocopying, we anticipate that the TAC may well only see black and white smudges in the above image. The ICL substructure *is* there, and can easily be seen in the FITS images. It's there. Trust us on this one.)

References

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Calcáneo-Roldán, C., Moore, B., Bland-Hawthorn, J., Malin, D., & Sadler, E. M., 2000, *M.N.R.A.S.,* **314,** 324.

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Feldmeier, J.J., Ciardullo R., & Jacoby G.H. 1998, *Ap. J.,* **503,** 109

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Gonzalez, A.H., Zabludoff, A.I., Zaritsky, D.& Dalcanton, J.J. 2000, *Ap. J.,* **536,** 561

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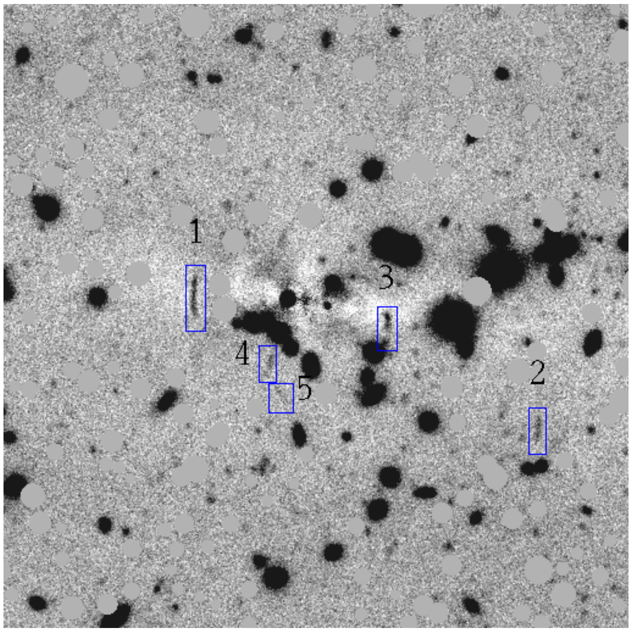

Figure 2: An image of the central region of Abell 1413, with the cD galaxy subtracted, and stellar sources masked out. Two arc-like structures are clearly visible (1, 2), with another three (3-5) possible. However, these structures are shorter ($\sim$ 10 kpc), and higher surface brightness ($\mu \sim 25$ mag arcsec^{-2}) than the debris arcs seen in Coma and Centaurus. Additionally, at least three of the arc candidates lie tangentially to the cD, suggesting that these arcs may be due to strong lensing. Gravitational arcs in clusters are uncommon at these redshifts (Fort & Mellier 1994), but some have been observed (e.g., Blakeslee & Metzger 1999). This may indicate that long tidal debris arcs are relatively rare, but with only a few clusters observed thus far, any conclusions are premature.

Oemler, A. 1976, *Ap. J.,* **209,** 693

Richstone, D.O., & Malumuth, E.M. 1983, *Ap. J.,* **268,** 30

Schombert, J.M. 1986, *Ap. J. S.,* **60,** 603

Trentham, N. & Mobasher, B. 1998, *M.N.R.A.S.,* **293,** 52

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (limit text to one page)*

Our program is aimed at studying the ICL in clusters possessing a variety of structural properties, in order to probe the relationship between the ICL and cluster environment. The role of the KPNO 2.1-m is to extend the reach of our study out to more distant, rich Abell clusters, to include the denser cluster environments in our studies. This will allow us to survey a wide range of cluster environments, giving us a large baseline from which we can study the link between ICL properties and cluster environment. The observations proposed here will study six Abell clusters within redshifts z=0.1–0.175 and differing Bautz-Morgan classification (mainly types I and II). The lower end of the redshift range is chosen such that the inner ~ 0.75 Mpc of the cluster fits on the 2.1-m FOV, allowing us to study the cluster as a whole without mosaicing, and permitting a reasonable amount of sky at the outer edge of the field for sky subtraction. The upper limit is set so that $(1+z)^4$ surface brightness dimming is not prohibitive, and also to prevent the angular size of the arcs from being too small. We will draw the target clusters once the observing dates are known. Arcs in the Coma cluster such as that studied by Trentham and Mobasher (1998) are at surface brightnesses of $\mu_V = 25.5$ and brighter. We aim to reach one magnitude fainter. In order to reach reliably to these surface brightness levels, we need to take great care with flat-fielding, sky subtraction and scattered light. These issues are discussed in the Technical Description section.

Our choice of the 2.1m telescope for this program (with its relatively small 10 arcmin field of view) requires some justification. A telescope with a larger field of view would be better, but unfortunately there are sources of systematic error on the available telescopes with larger field of view. The WIYN's Nasmyth design and open tube provides many paths for light to reach the detector in addition to the traditional one via primary, secondary and tertiary mirrors. The problem is so acute that twilight flats are not used for flatfielding on WIYN because of the amount of scattered light from the dome and sky that reaches the detector. Our application is many times more sensitive to scattered light problems than usual programs. Baffling WIYN would be extremely difficult, if not impossible. While the 2.1m also has an open tube, its smaller field of view is easier to baffle correctly. While the 4m/Mosaic has a much larger field of view, it currently has SITe CCDs. These chips suffer from large-scale wavelength-dependent QE variations of order 5-10% which limit flat-fielding accuracy to 1% at best, ten times too large for our program.

Another concern is the removal of scattered light from bright stars. This is an important part of our analysis which is described in Morrison, Boroson and Harding (1994), where we modeled the wings of the stellar image out to two arcmin from its center. The exact behavior of the extended wings is a mix of scattering in the atmosphere, optical surfaces, and also multiple reflections from each surface, which generate out of focus images on the CCD. With the higher QE and better AR coating of the T2KA CCD, scattered light from bright stars will be significantly reduced compared to earlier researchers. Also, we will further minimize scattered light from stars outside the field of view by using a mask outside of the dewar window. Nonetheless, even with all these precautions, we still select clusters carefully, making sure there are no bright stars in the CCD field or close to it: approximately half of our candidate clusters were rejected for this reason.

Use of Other Facilities *Describe how the proposed observations complement data from non-NOAO facilities. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program.*

This project is a pilot survey intended to detect intracluster starlight, and define its basic properties. Our intention is to collect a small, representative, sample of galaxy clusters at a redshift of 0.2. Once this sample is completed, we plan to begin a lower redshift ICL survey on the private Case Western Burrell Schmidt telescope. When necessary upgrades are completed on the Schmidt (expected this fall), we intend to perform similar surveys for ICL in nearby galaxy clusters, including the Virgo cluster, and the M81 group.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the PI during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

$\boxed{\star}$ 3.5 nights at the KPNO 2.1-m, Direct Imaging, April 2000. First observations of this survey. Obtained good data on two clusters, Abell 1413 & MKW 7. Data has been reduced, and the 1 σ value of the flat-fielded sky is $\mu_V = 26.0$ mag/sq arcsec. By using our standard techniques of masking and binning, we have achieved our planned surface brightness limit of $\mu_V = 26.5$. Additionally, we performed a number of tests at the telescope to insure that our results would not be dominated by systematic errors. Data on Abell 1413 and MKW7 was presented as a poster at the January 2001 AAS meeting (BAAS 32, p. 1579), and a paper on these first results has been submitted to the Ap. J.

$\boxed{\star}$ 7 nights at the KPNO 2.1-m, Direct Imaging, August 2000. The monsoon killed us, combined with telescope runaways. We lost three nights totally to weather, 1.5 nights due to telescope/dome problems. Sky was non-photometric the entire time, keeping us from obtaining any useful surface brightness data.

$\boxed{\star}$ 5 nights at the KPNO 2.1-m, Direct Imaging, June 2001. Once again, the monsoon killed us. We opened the telescope only on the last night, with non-photometric conditions. Obtained a few test image of clusters, but no scientifically usable data obtained.

$\boxed{\star}$ 7 nights at the KPNO 2.1-m, Direct Imaging, March 2002. We had a successful run. Obtained high quality on first two nights on two clusters: Abell 1234 and Abell 1914. Due to high winds and wind shake, the effective seeing degraded to 2 arc seconds on the next three nights. Nonetheless, we obtained marginal data on a third cluster, Abell 1553. Clouds on the final two nights caused us to switch to backup projects.

The P.I. has also been involved with studies of planetary nebulae as distance indicators, and as probes of the intracluster light in Virgo:

KPNO 4-m (4 nights, April 2002): ??

KPNO 4-m (3 nights, April 2001): The properties of intracluster starlight in the Virgo cluster, and the M81 group: Data was taken, although the seeing was relatively poor. A poster paper on the M81 data was presented at the IAU planetary conference in November 2001.

KPNO 4-m (1 night, Feb 2000): A Planetary Nebulae Distance to NGC 4258: Clouded out. No useful data obtained.

Observing Run Details for Run 1: KP-2.1m/CFIM + T2KA

Technical Description *Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for WIYN-2hr, WIYN-SYN, YALO, and Gemini runs).*

Flat-fielding

Flat-fielding needs to be extremely accurate, particularly over large distances on the CCD. This requirement dictates our choice of telescope as other possibilities such as the 4m/0.9m/Mosaic are equipped with SITe 2k/4k back-illuminated CCDs which have significant color-dependent large-scale flat-field variations across the chip, which mean that flat-fields more accurate than 1–2% are impossible with these chips. This is because when the large-scale flatfield pattern varies with wavelength, you need to know ahead of time what color light to use to make the flat-field (eg from dark sky, twilight or dome) and this is impossible since the objects being studied vary in color.

We choose to use dark sky exposures taken at similar telescope position to the object exposures to make our flat fields, and need of order 20 such exposures to make a useful flat (Morrison et al 1994, on the KPNO 0.9m, took 22 dark-sky exposures of 30 mins each and reached to surface brightness levels of $\mu_R = 26$, $\mu_B \sim 27.5$ with six half-hour object exposures. From our first run on the 2.1m, we obtained a total of 20 dark sky exposures to obtain our surface brightness limit of $\mu_V = 26.5$)

Scattered Light

We need to make sure that the only light which falls on the CCD comes via the regular optical path, or the flat fields that we make will be useless. The ability to baffle the tube of the 2.1m is advantageous here, and we have already spent a significant amount of time testing and removing scattered light on this telescope. We also take care not to choose clusters with nearby bright stars or planets.

Sky subtraction

This is more problematic. Ideally, we need clusters which fit onto the CCD with clear sky on all sides, so an accurate estimate of the background sky can be made using the CCD image itself. We have found that at the faint surface brightness levels we work at, the night sky is variable on the timescale of minutes, so offset sky exposures are not possible.

However, clusters which fit entirely onto the 2.1meter's 10 arcmin field are so distant ($z > 0.2$) that arcs such as the ones detected in Coma would cover only a small number of pixels, reducing their detectability.

Thus we have compromised by selecting clusters which largely fit on the CCD, but not entirely. If there is significant diffuse ICL at the edges of these clusters, we will subtract it in our sky-subtraction process. But we will be able to detect centrally concentrated diffuse light and smaller features such as arcs and set limits on their surface brightness.

Also, we need to work in a filter where background sky is not very bright (such as I) but where there are enough sky photons to make dark sky flats that are not limited by photon statistics (as they might be in B). V is a good compromise, and we have chosen the Washington M filter because it has a similar passband to V but avoids the 5577 night sky line.

Exposure times In order to reach surface brightness levels of μ_V=26.5, we need 3 hours per object, and ten hours total of dark sky flat observations. It is useful to break these exposures up into 15-minute single exposures so that the object can be "dithered" on the CCD to reduce flat-fielding errors further. Assuming 5 minutes of overhead (readout, setup, dithering) per exposure means we need 4 hours per object plus 14 hours total of sky exposures and several more hours for observing standards, etc.

This brings our requirement to 7 nights. Dark time is essential to our project because the sky brightness needs to be as low as possible so we can detect these extremely faint features. Additionally, we require photometric conditions to avoid problems with scattered light off of clouds, which can be many times higher than the ambient sky brightness. We will not be able to take observations with the moon above the horizon, or with clouds in the sky.

Morrison, H., Miller, E., Harding, P., Stinebring, D. & Boroson, T. 1997, *A. J.,* **,** 113, 2061

Fry, A. Morrison, H., Harding, P. and Boroson, T. AJ, 118, 1209 (1999)

Instrument Configuration

Filters: Washington M - KP1581	Slit:	Fiber cable:
Grating/grism:	Multislit:	Corrector:
Order:	λ_{start}:	Collimator:
Cross disperser:	λ_{end}:	Atmos. disp. corr.:

R.A. range of principal targets (hours): 18 to 6

Dec. range of principal targets (degrees): 0 to 50

Special Instrument Requirements *Describe briefly any special or non-standard usage of instrumentation.*

NOAO observing proposal LaTeX macros v2.6.