NOAO Observing Proposal *Standard proposal* **Panel:** *For office use.*
Date: September 29, 2000 **Category:** Clusters of Galaxies

The Properties of Intracluster Light

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

We propose to search for and quantify the properties of the intracluster light (ICL) in galaxy clusters as a function of cluster environment. The ICL is likely formed through tidal stripping of cluster galaxies, so that its properties should be linked both to the dynamical evolution of the cluster and to the distribution of dark matter in cluster galaxies. The structure of the ICL, therefore, should vary between clusters with different physical properties. We will target six rich Abell clusters which span a range of Bautz-Morgan type, from cD-dominated type I clusters to type III clusters where the galaxy population is more uniform. Inasmuch as the presence or absence of a central cD is a signature of the degree of dynamical evolution of a cluster, this sample allows us to probe how the properties of the ICL depend on the cluster's dynamical state. We are requesting 5 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	5	darkest	Feb - May	Feb - Jul
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). However, the ICL provides a direct way to study these different mechanisms. Depending on the dynamical state of the cluster environment, the ICL can contain anywhere between 10% and 70% of the cluster's total luminosity (Richstone & Malumuth 1983; Miller 1983). Furthermore, the distribution of stripped ICL is sensitive to the fraction of cluster dark matter found in galaxies versus that distributed diffusely throughout the cluster. If cluster galaxy dark halos are tidally truncated, stripped material can be unbound from the galaxies and distributed throughout the cluster. Conversely, if cluster galaxy halos survive, tidally stripped material will remain bound, leaving galaxies embedded in very low surface brightness "cocoons" (e.g., Mihos *et al.* 1998; Fig. 1). The ICL is therefore a sensitive probe of the mechanics of tidal stripping, the distribution of dark matter around galaxies, and cluster evolution in general.

Recently, the study of intracluster starlight has increased dramatically due to the detection of individual intracluster stars in nearby galaxy clusters (e.g., Theuns & Warren 1997; Ferguson *et al.* 1998; Feldmeier *et al.* 1998). Collectively, these observations show that the ICL is present in galaxy clusters at a significant level (at least $\sim$ 20% of the total cluster starlight), and is scattered non-uniformly throughout the clusters. However, although the presence of intracluster stars has been demonstrated, there is little information on how the amount and distribution of intracluster starlight varies with the properties of the cluster it inhabits. We do not yet have a global picture of the prevalence of the ICL in galaxy clusters, nor of the information it contains about the dynamical state of clusters, both of which are crucial in developing more advanced models of cluster evolution.

The most direct way to study ICL is through very deep imaging of a variety of galaxy clusters. Although direct imaging of the ICL is difficult, it is the only way to gain a global picture. We have demonstrated the suitability of the 2.1m for deep surface photometry on our first run (see Figure 2), and we propose to continue our program to search for the ICL in a sample of Abell and MKW/AWM galaxy clusters. The clusters are chosen to include a range of cluster environments, in order to relate the properties of the ICL to the dynamical properties of clusters. For example, well evolved, rich clusters like Coma will have experienced continuous stripping and dynamical mixing and may have significantly more ICL than irregular unrelaxed clusters such as Virgo. With the Burrell Schmidt we plan to search for the ICL in nearby loose groups and the Virgo cluster; the study proposed here will complement the Schmidt study by focusing on more dense environments.

While the total amount of ICL in clusters is of great interest, we will also focus our attention on the presence of *morphological substructure* in the ICL. One prediction of the "galaxy harassment" model of Moore *et al.* (1996) is that starlight arcs should be present in many galaxy clusters. 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. These arcs suggest that material has been readily stripped from galaxies as they moved through these clusters. Such stripping occurs most efficiently for galaxies with tidally truncated halos. However, in poorer, less evolved clusters, the halos may not be so severely limited, and these cluster-wide arcs may be much rarer. From our observations, we will be able to place limits on the frequency and properties of these arcs in a well-defined sample of galaxy clusters. In conjunction with our ongoing dynamical modeling of cluster galaxies, these observations will constrain the distribution of dark matter in different cluster environments.

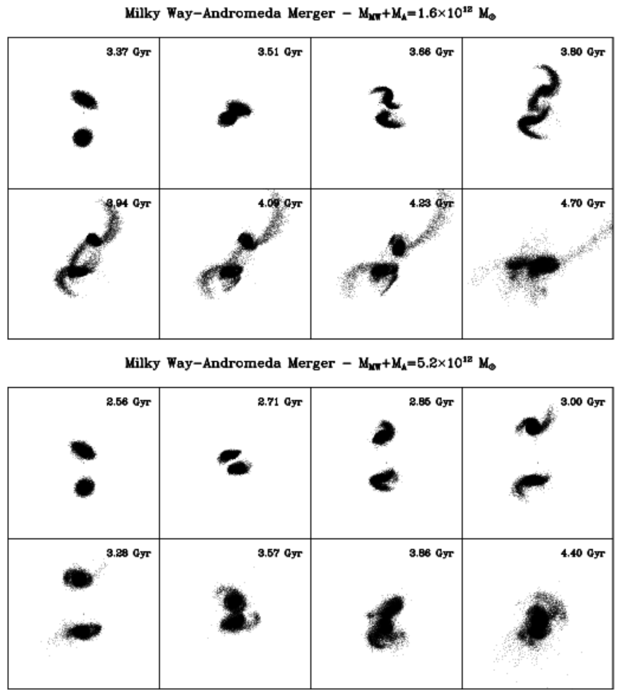

Figure 1: Galaxy collision simulation from Dubinski *et al.* 1996. In the upper panels, the dark matter halos are smaller and lower in mass and compact, as might be expected due to tidal losses in an evolved cluster. In these types of encounters, stripped material is lost from the galaxies in long tidal streams. The lower panel shows an encounter where the halos are more massive and extended, and here the stripped material remains tightly bound to the galaxies.

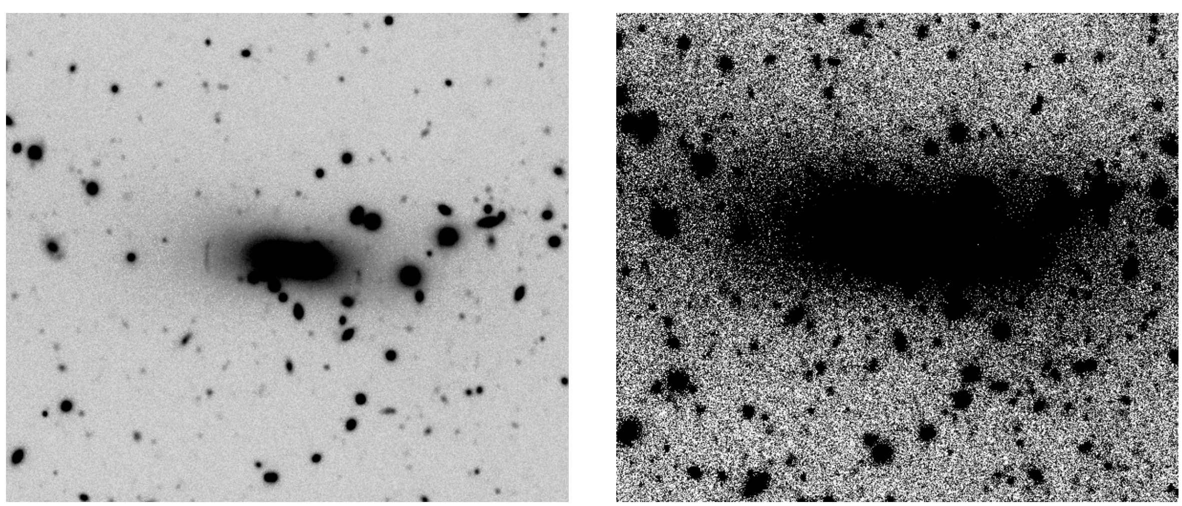

Figure 2: On the left is the central portion of our combined, flat-fielded image for Abell 1413, taken in our first telescope run on this program. Two arc-like structures can be clearly seen to the left and the lower right of the central cD galaxy. Although in this case, these arcs may be features intrinsic to the cD galaxy, they are analogous to the arcs we are searching for in the intracluster environment. On the right is the same region with the greyscale stretched. Although the galaxies have not been subtracted from this image, note the extreme flattening to the cD + intracluster light.

References

Dressler, A. 1984, *Ann. Rev. Astr. Ap.,* **22,** 185

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

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

Ferguson, H.C., Tanvir, N.R., & von Hippel, T. 1998, *Nature,* **391,** 461

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

Gregg, M. D. & West, M. J. 1998, *Nature,* **396** 549.

Miller, G.E. 1983, *Ap. J.,* **268,** 495

Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A. 1996, *Nature,* **379,** 613.

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

Theuns, T., & Warren, S.J. 1997, *M.N.R.A.S.,* **284,** L11.

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. List all telescopes on which you have applied for or been granted time for observations related to this project. For each, indicate the nature of the observations, and describe the importance of the observations proposed here in the context of the entire program. (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. For nearby groups and clusters, the wide field of the Burrell is ideal for these objects. We are currently upgrading the Burrell to optimize it for these types of observations (and have dedicated time on this instrument once the upgrades are complete). 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 a small but significant number of six Abell clusters within redshifts z=0.1–0.175 and differing Bautz-Morgan classification (I, II, III). 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: a sample of candidate objects is given below. Arcs in the Coma cluster such as that studied by Trentham and Mobasher (1998) are at surface brightnesses of $\mu_B = 26.5$ 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. CWRU's Burrell Schmidt and the 4m/Mosaic have much larger fields of view, but both currently have 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 modelled 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.

Previous Use of NOAO Facilities *List allocations of telescope time on facilities available through NOAO to the Principal Investigator 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.*

$\star$ 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 & MKW7. 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 will be able to achieve our planned surface brightness limit of $\mu_V = 26.5$. Analysis is ongoing. Additionally, we peformed a number of tests at the telescope to insure that our results would not be dominated by systematic errors. We found one bright scattered light feature that occurred for some candidate clusters. With the help of KPNO staff, the source for this scattered light was identified as due to a grazing incidence off of the NW spider vane.

$\star$ 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. Spent the 2.5 non-photometric nights on backup science and preliminary images of the target clusters for future runs. We also spent significant time conducting tests for, and removing sources of, scattered light in the 2.1m optical path. This masking has removed the scattered light feature from our first run, as well as several other smaller sources of scattered light.

Why CTIO? *(For CTIO proposals only.) Explain why access to the southern hemisphere is needed to achieve your scientific goals.*

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 Burrell Schmidt and 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 of 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 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 of sky exposures and several more hours for observing standards, etc.

This brings our requirement to 5 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. We will not be able to take observations with the moon above the horizon.

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
Grating/grism:
Order:
Cross disperser:

Slit:
Multislit:
$\lambda_{\rm start}$:
$\lambda_{\rm end}$:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.:

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

Target Table for ICL Survey

Obj ID	Object	α	δ	Epoch	Mag.	Filter	Exp. time	# of exp.	Lunar days	Sky	Seeing	Comment
1	ACO 1132	10:58:18	+56:46	2000.		M			0			
2	ACO 1234	11:22:24	+21:23	2000.		M			0			
3	ACO 1553	12:30:48	+10:34	2000.		M			0			
4	MKW 6	14:17:36	+02:02	2000.		M			0			
5	ACO 1914	14:26:00	+37:49	2000.		M			0			