Intracluster Planetary Nebulae in Clusters and Groups

John J. Feldmeier
Department of Astronomy, Case Western Reserve University,
Cleveland, OH, USA

Robin B. Ciardullo
Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA

George H. Jacoby
WIYN Observatory, Tucson, AZ, USA

Patrick R. Durrell
Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA

J. Christopher Mihos
Department of Astronomy, Case Western Reserve University,
Cleveland, OH, USA

Abstract. We present the results from multiple surveys for intracluster planetary nebulae (IPNe) in nearby galaxy clusters and groups. We find that in the case of clusters, our observations imply: 1) the amount of intracluster starlight is significant, up to 20% of the total starlight, 2) the Virgo Cluster is elongated along our line of sight, and 3) the intracluster light is clustered on the sky, implying ongoing tidal stripping. In contrast, searches for IPNe in groups have found little or no intra-group population, implying there may be something in the cluster environment that significantly enhances intracluster star production. From high-resolution N-body simulations, we find that the IPNe should create observable features in position-velocity space, and that these features may eventually allow us to place limits on the dynamics of galaxy clusters.

1. Introduction

The study of intracluster starlight (ICL) has grown dramatically in the last few years. Once thought to be just another odd prediction of Zwicky (1951), intracluster starlight may be a useful tool in understanding the evolution of galaxies in clusters, and may be an important chain in the recycling of intergalactic and interstellar matter (see Arnaboldi, this conference for a review).
In particular, intracluster planetary nebulae (IPNe) are an excellent tracer of the intracluster light, and can be detected relatively easily in nearby galaxy clusters with deep narrow-band imaging. Extragalactic planetaries appear as point sources through a [O III] $\lambda 5007$ narrow-band filter, but disappear altogether when imaged through a “off-band” filter. Planetary nebulae also follow the [O III] $\lambda 5007$ planetary nebulae luminosity function (PNLF), which is a highly accurate distance indicator (see Ciardullo et al. 2002b and references therein). The well-defined luminosity function allows us to gather depth information on the intracluster stars. Finally, since IPNe are emission-line objects, their radial velocities can be determined with moderate-resolution spectroscopy (Freeman et al. 2000), allowing us to obtain crucial dynamical information.

Here, we focus on our group’s efforts to search for IPNe in nearby galaxy clusters and groups, and give a brief summary on the results to date. It is important to stress that surveys for IPNe are not pristine: we estimate that about 20% of our IPNe candidates in Virgo are actually Lyman-α galaxies at $z = 3.1$ (Ciardullo et al. 2002a).

2. Studies in Clusters

IPNe were first discovered in the Virgo cluster as a population of “overluminous” planetary nebulae, though they were not originally recognized as such (Jacoby, Ciardullo, & Ford 1990). Kinematic proof of IPNe was then found by Arnaboldi et al. (1996), and IPNe were subsequently detected in the Fornax cluster by Theuns & Warren (1997). Additional evidence for large numbers of IPNe in front of the Virgo elliptical M 87 quickly followed (Ciardullo et al. 1998). With the advent of wide-field mosaic detectors, it became feasible to observe much larger portions of the Virgo and Fornax clusters for IPNe.

Figure 1 shows the status of our surveys to date. We have detected 318 IPNe candidates in the Virgo cluster (Feldmeier, Ciardullo, & Jacoby 1998; Feldmeier et al. 2003; Feldmeier et al. 2004), and 95 candidates in the Fornax cluster (Ciardullo et al. 2004). Transforming the numbers of IPNe to a stellar luminosity is complicated by several factors: the amount of background contamination, the known density differences of PNe to stellar luminosity (Ciardullo 1995), and any line-of-sight effects (Feldmeier et al. 2004). However, if we take conservative limits for such effects, we find that both clusters contain 10–20% of their stars in an intracluster component.

The spatial distribution of IPNe in the cluster is also of great interest, since PNNe closely follow the starlight in galaxies (Ciardullo et al. 1989). For instance, in Virgo we can find the upper limit distance to each IPNe field using the sharp cutoff of the PNLF. We can then compare these distances to the PNLF distances of the cluster ellipticals (Jacoby, Ciardullo, & Ford 1990; Ciardullo et al. 1998) and to the HST Cepheid distances of spirals (Freedman et al. 2001). As demonstrated in Figure 2, the IPNe are enormously extended, up to 3 Mpc in depth. This agrees with the inferred depth of Virgo’s spiral galaxies (derived from the Tully-Fisher observations; Solanes et al. 2002), and suggests that the bulk of the IPNe come from late-type galaxies.

When we compare the IPNe density in Virgo and Fornax to that of the galaxies directly, we find that in both clusters, the amount of IPNe may drop
more slowly with radius than that of the galaxies, though the scatter is large due to small numbers. From observing the positions of the IPNe on the sky, we also gain some insight on the spatial distribution of the ICL. We find that the IPNe are clustered on arcminute scales, implying that there is ongoing tidal stripping in these clusters.

3. Studies in Groups

Although the amount of intrachannel starlight in clusters such as Virgo and Fornax is now well established, the amount of ’intra-group’ starlight is still uncertain. Theoretical studies predict that if most intrachannel stars are removed by galaxy collisions (e.g., Richstone & Malumuth 1983; Moore et al. 1996), the fraction of intra-group stars, to first order, should be a smooth function of galaxy number density ($L_{ICL} \sim N_{Gal}^2$).

To test this hypothesis, we have undertaken a large-scale [O III] $\lambda$5007 IPNe survey of the nearby M 81 group of galaxies. This galaxy group is known to be strongly interacting, with multiple tidal tails seen in H I gas (Yun, Ho, & Lo 1994). We have surveyed 1.44 square degrees of this system with the KPNO 4-m and the Mosaic camera, and have reached at least two magnitudes down the PNLF in all of our fields.

Although the analysis is ongoing, there is already a clear result: there is substantially less IPNe in the M 81 group than in the rich clusters. For example, if we take the results from our Field 1, we find 102 PNe candidates near M81 proper, but no objects whatsoever in the remaining half of the field. If we assume this density limit is typical, and adopt a limit of $1 \pm 1$ intra-group PNe this leads us to a intra-group fraction of 1.3%. These results are strengthened by a deep broad-band survey of the M81 group to look for intra-group red giant stars which find a similarly small limit (see Durrell, this volume).

Our result, combined with a similar result for the Leo I Group (1.6%; Castro-Rodríguez et al. 2003), strongly implies there is substantially less (4–15 times) less intergalactic stars in groups than there are in clusters. The drop in density is unexpected, and will need to be explained by models of intracluster star production (see Ciardullo, this volume).

One of the motivations for surveying the M81 and Leo I systems for intra-group PNe is that both these groups contain a network of H I tidal features (Schneider et al. 1989; Yun, Ho, & Lo 1994). However, no correlation has been found between the H I gas and the IPNe. It may be that for normal spiral galaxies, tidal interactions can remove the H I in the outer galaxy without causing any of the stars in the inner regions to escape. IPNe observations in at least one undisturbed galaxy group would be helpful to ensure this result.

4. Dynamical Studies of Intracluster Light

Large samples of IPNe are already available for a radial velocity measurements, and many more will be found in the near future. Consequently, it is important to understand the kinematics of the ICL. Several groups have already begun the process of modeling the velocity structure of the ICL through a variety of simulations (Moore et al. 1996; Dubinski, Murali, & Ouyed 2001; Napolitano
Figure 1. Regions of the Virgo (left) and Fornax (right) clusters, drawn from the Digital Sky Survey, with the location of our IPN survey fields marked. Arrows represent additional detections of ICL made by other researchers. Thus far, we have found a total of 413 IPN candidates in both clusters, but we have observed less than 1% of each cluster.

et al. 2003). In these models, the intrachuster light generally follows a radial orbit distribution, but is dynamically unrelaxed, and fills the observed phase space non-uniformly, due to the presence of tidal debris. The radial orbit envelope may allow us to estimate the mass profile of galaxy clusters (Dubinski, Murali, & Ouyed 2001), independent of more traditional methods. Moreover, since the phase-space clumpiness of the ICL is related to the cluster’s dynamical age, the simulations, combined with the IPN observations, will allow us to place interesting limits on this quantity, as well as potential limits on cosmological parameters.

To improve upon the situation, we have constructed our own high-resolution, fully-self consistent N-body models, using large scale structure simulations. We use the simulations to find proto-clusters at high redshift, replace the low resolution galaxies with self-consistent galactic models (Hernquist 1993), and run the simulations. We confirm the general results thus far: our ongoing focus is on developing useful metrics for observations.
Figure 2. The upper-limit distances to our and other IPNe fields compared to PNLF distances of elliptical galaxies and HST Cepheid distances of spirals. As is clearly seen, some of the IPN are up to 3 Mpc in front of the Virgo Cluster core. The various subclumps of Virgo (A & B) are denoted for each IPNe field.
References

Arnaboldi, M. et al. 1996, ApJ, 472, 145
Arnaboldi, M. et al. 2002, AJ, 123, 760
Castro-Rodíguez, N., et al. 2003, A&A, 405, 803
Ciardullo, R. 1995, in IAU Highlights of Astronomy, 10, ed. I. Appenzeller (Dor- drecht: Kluwer), p. 507
Ciardullo, R. 1995, in IAU Highlights of Astronomy, 10, ed. I. Appenzeller (Dor- drecht: Kluwer), p. 507
Ciardullo, R., Jacoby, G.H. & Ford, H.C. 1989, ApJ344, 715
Ciardullo, R., et al. 1998, ApJ, 492, 62
Ciardullo, R., et al. 2002a, ApJ, 566, 784
Ciardullo, R., et al. 2002b, ApJ, 577, 31
Dubinski, J., Murali, C., & Ouyed, R. 2001, unpublished preprint
Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1998, ApJ, 503, 109
Feldmeier, J. J., et al. 2003 ApJS, 145, 65
Feldmeier, J. J., et al. 2004 ApJ, in prep
Freedman, W. L. et al. 2001, ApJ, 553, 47
Freeman, K. C. et al. 2000, ASP Conf. Ser. 197, (San Francisco: ASP) 389.
Hernquist, L. 1993, ApJS86, 389
Jacoby, G. H., Ciardullo, R., & Ford, H. C. 1990, ApJ, 356, 332
Moore, B., et al. 1996, Nature, 379, 613
Napolitano, N.R., et al. 2003, ApJ, 594, 172
Okamura, S., et al. 2003, PASJ, 54, 883
Richstone D. O., & Malumuth, E.M. 1983, ApJ, 268, 30
Schneider, S. et al. 1989, AJ97, 666
Solanes, J. M., et al. 2002, AJ, 124, 2440
Theuns, T., & Warren, S. J. 1997, MNRAS, 284, L11
Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1994, Nature, 372, 530
Zwicky, F. 1951, PASP, 63, 61
This figure "fornax_bm.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0310884v1
This figure "ipn_bm.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/0310884v1