INTRACLUSTER GLOBULAR CLUSTERS

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ABSTRACT

Intracluster globular clusters (IGCs) are expected to exist in the cores of clusters of galaxies. A computer program was created to generate models that will be used to match the distributions of unresolved objects in deep images of clusters within the globular cluster magnitude range at the distance of the cluster, and tested using a two dimensional, two-sample Kolmogorov-Smirnov test for compatibility. This computer program can be applied to any cluster if the location of the X-ray centroid has been determined and the number of unresolved objects is known. This is the most efficient test to determine if IGCs exist in galaxy clusters. The discovery of IGCs would provide new insights to galaxy evolution in dense environments, and to the dynamical processes that have affected galaxies over the age of the universe. The discovery of a population of IGCs would also provide a new and independent tracer of dark matter distribution in the cores of galaxy clusters. Intial test runs of the program show that it is very capable in determining a close match to the parameters of the original distribution.

INTRODUCTION

The myriad of components in clusters of galaxies has grown in recent years. From the galaxies of stars to hot X-ray emitting gas to dark matter, these new components have been identified and studied and with it came new knowledge of how the clusters have changed over time and what was currently going on in these large groups of galaxies. A new component has recently been proposed to help explain some new questions that have arisen in the study of galaxy clusters. These intracluster globular clusters, if they exist, need to be studied just as muc as any other component of the cluster in order for clusters of galaxies to be better understood. Without a clear understanding of how the individual parts of the cluster behave, predictions of the future of clusters as well as determining the histories of the clusters can never be fully realized. These objects could provide an understanding of cluster dynamics, be used to investigate star formation, and trace the dark matter distribution of the cluster. Intracluster globular clusters could also explain the large amount of globular clusters seen around giant elliptical galaxies in rich clusters.

Globular clusters (GCs) are thought to be among the oldest stellar systems in the universe. These objects are large, dense collections of stars that are found in the halos of most galaxies. GCs are ideal for studying the history of their surroundings because they are believe to be some of the first stellar systems formed. The composition of GCs and their orbital dynamics about their parent galaxy can provide much information on the evolution of the par galaxy and clues to the formation process. GCs have also been detected around galaxies outs our local group in many other clusters of galaxies. These extragalactic GCs have been established as tracers of the formation and evolution of galaxies.

Clusters of galaxies are some of the largest structures in the universe. In order to understand clusters of galaxies, specifically their histories and evolution, the characteristics the components must be understood as well as their interactions. The idea of GCs in a galaxies that did not belonging to a specific galaxy potential was first suggested by Whi and then later expanded on by West *et al.* (1995) in order to explain the unusually large systems surrounding several large elliptical galaxies in clusters. White argues that GCs stripped along with the stars and create a population that belongs strictly to the cluster po When a central galaxy is then observed, the intracluster population is overlaid onto the GC population. It should be noted that IGCs have not been directly observed. However, whether these objects exist or not is not a trivial question. If these GCs exist, they can be examine the dynamical history of the galactic components of the cluster.

METHOD

The most efficient way to test for the existence of IGCs is to try to recreate the distribution of unresolved objects in deep images of the clusters and compare the models to original data. The expected distribution of the unresolved objects falls in two components, background galaxies and faint stars in our own galaxy that are randomly distributed across th field and a centrally distributed component of GCs that follows a King profile. The models can be compared to the original data with a two-dimensional adaptation of the Kolmogorov-Smirnov test (KS test) for goodness-of-fit. The KS test determines the "greatest absolute difference between two cumulative distributions" (Press *et al.* 1992). This quantity is returned from the KS test as a statistic, called the "D" statistic, which can then be compared numerically to other "D" statistics from other models. The KS test actually measures the poorness-of-fit so higher values of the "D" statistic imply that the two distributions are different.

Deep images of the cores of several clusters have been obtained. The richest of these clusters is the Coma Cluster, which allows for the possibility of a large population of GCs around the core of the cluster. In April 2000, deep *R*- and *I*-band CCD images of the center of the Coma cluster of galaxies were obtained by Michael West (UH Hilo) and Michael Gregg (UC Davis) using the 3.6m Canada-France-Hawaii Telescope on Mauna Kea with the CFH12K mosaic camera for a total exposure of two hours in each filter. *Hubble Space Telescope* (*HST*) images of the Coma cluster were also obtained by West and Gregg with WFPC2 and STIS in cycle 9. These extremely high resolution images will be used to provide supporting evidence for any IGC candidates that may be found. West and Gregg are currently working on producing a catalogue of faint objects detected in these images.

Michael West also has data for other clusters that would also serve as good fields for testing for the existence of IGCs. Abell 1185 is another cluster that provides for an excellent opportunity to look for IGCs. West has wide field Keck I images in several colors, as well as deep, small field HST images of just the core of the cluster. Data of the Virgo cluster from the 8.3m Subaru telescope on Mauna Kea would be another excellent test for the IGC model since it is even closer then the Coma cluster.

Models are created in order to recreate the distribution of unresolved objects found in deep images of the cores of galaxy clusters. These models will consist of two components; one belonging to a random background and one that is centered on the dynamical center of the cluster. The dynamical center of the cluster can be determined from either studying the motions of the galaxies in the cluster or by tracing the distribution of X-ray emitting gas. The centrally distributed component will also have the core radius, which is the radius at which the number of globular clusters is one-half, as another component of the model. The models will be compared to the data using a two-dimensional adaptation of the KS test. The existence of IGCs could then be determined based on the comparison of the models and the data.

THE COMPUTER PROGRAM

The computer code is needed to create and model two-dimensional distributions efficiently and effectively. The program simulates the distribution of objects that is expected in the cores of galaxy clusters and then, the similarity between the models and the data obtained of the clusters is tested using the two-dimensional KS test. Each model has three parameters, a percentage random background, a percentage King profile, and a core radius to go with the King profile distribution. Each model is also run a specified number of times to average out any variations. An input file gives the program the necessary starting parameters and an output file is generated returning the results for each model.

In the real data obtained of the cores of the galaxy clusters to be studied, the galaxies and other resolved objects in the field, such as bright stars in our own galaxy, will be removed from the field so only the unresolved objects are left. The models generated will also have these sections removed as well. If any data point in the model falls into one of these cutout regions, it will be discarded and another point generated.

The two-dimensional, two-sample KS test routine used in the program was obtained from Press et al. (1992, p. 649). The routine also employs several other support subroutines from various other parts of the book. The random number generator was also obtained from Press et al. (1992, p. 283) called "ran 3". This random number generator is based on a subtractive method rather then the normal adding method used by most other random number generators.

The IGC component is based on the idea that any globular clusters stripped from other galaxies or formed directly out of the intracluster medium would settle in the potential well of the cluster following a King profile distribution. The King approximation of a bounded isothermal sphere is

$$\sum(r) = \frac{\sum_0}{1+\frac{r^2}{r_c^2}}, \tag{1}$$

where $\sum(r)$ is the projected mass density at a distance r from the galaxy cluster center, $\sum_0$ is the central density, and r_c is the core radius. The central density is a constant that only depends on the total number of objects in the distribution. The more objects there are, the higher the central density. The core radius, however, is the distance from the center at which the number of objects falls to one-half. A lower core radius means that most of the objects are concentrated towards the center while a higher value implies that the objects are more dispersed.

In order to obtain a method of generating the radial component in the computer program, a function of a uniform random distribution that gives the radius under the King profile is needed. This is accomplished by noticing that the cumulative distribution function (cdf) of a continuous function is equal to a uniform random number distribution. To find the cdf, the probability distribution function (pdf) is needed. The

$$pdf = \frac{\sum(r)}{c}, \tag{2}$$

where $\sum(r)$ is the King profile distribution (1) and the normalization constant c is found by integrating the King distribution from zero to some large r_{max}

$$c = \int_0^{r_{\max}} \frac{\sum_0}{1+\left(\frac{r}{r_c}\right)^2} dr = \tan^{-1}\left(\frac{r_{\max}}{r_c}\right)\cdot r_c \cdot \sum_0 . \tag{3}$$

In practice, r_{max} just needs to be larger then the field being created since r falls of rapidly under the King profile. With the pdf, the cdf can be found by integrating the pdf from zero to some arbitrary r, which is the radius of an object that will be generated

$$cdf = \int_0^r pdf\, dr = \frac{\tan^{-1}\left(\frac{r}{r_c}\right)}{\tan^{-1}\left(\frac{r_{\max}}{r_c}\right)} = u \tag{4}$$

where u is a random uniform distribution. By inverting the cdf, a radius under the King profile as a function of a random uniform distribution can be obtained

$$r(u) = r_c \cdot \tan\left(u \cdot \tan^{-1}\left(\frac{r_{\max}}{r_c}\right)\right). \tag{5}$$

In the program, the radius of an object in the IGC component is found by generating a large amount of random numbers using the same routine, "ran 3", as before, and then inputting it into (5). However, the King profile is a one-dimensional function that deals only with the radial position and not the angular position. To apply the King distribution to a two-dimensional field, the angular positions are generated randomly.

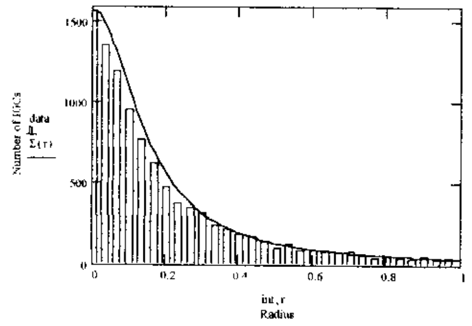

Figure 1. Histogram of generated points from a random number generator being conformed under a King profile distribution. It is graphed with the King distribution function (1). The bars represent the histogram and the solid line represents the King distribution function.

The effectiveness of the above method is demonstrated in Figure 1, which shows the King profile graphed with a histogram of data points generated under the above method. Ten thousand points were generated with a core radius of 0.15 and r_{max} was equal to 100. The units are arbitrary distances. When actual images are looked at, the distances will be scaled to go between zero and one. This graph only plots the radial positions since the angular positions are randomly generated. An excellent fit between the histogram of data points and the King profile is observed for all values of the radius.

Test Runs

In order to determine the effectiveness of the program, test runs need to be made using the program with artificial data. The testing phase of the project has only just begun, however, initial indications point towards the program being very effective in determining the correct parameters of the artificial data. When given a data set with unknown initial conditions, the program was able to find the correct distribution within a few percentage points. The determined value of the core radius was also within a very small margin of the correct value. One data set tested had initial parameters of 79% IGC population, 21% random background, and a core radius of 0.3. A section of the final output of the program is shown below. The best fitting distribution found was one with a 78% IGC, 22% random background population, and a core radius of 0.3.

Background %	IGC %	Background %	IGC %	Background %	IGC %
20	80	21	79	22	78
Core radius	D statistic	Core radius	D statistic	Core radius	D statistic
0.27	0.0319113	0.27	0.0284577	0.27	0.0269154
0.28	0.0287645	0.28	0.0282629	0.28	0.0246766
0.29	0.0273549	0.29	0.0251119	0.29	0.0239055
0.3	0.0259287	0.3	0.0247886	0.3	0.0222637
0.31	0.0232007	0.31	0.0233748	0.31	0.02301
0.32	0.0233624	0.32	0.0242662	0.32	0.0256509
0.33	0.0250622	0.33	0.0241915	0.33	0.024204
0.34	0.0245398	0.34	0.0260697	0.34	0.0256633

CONCLUSION

Further observations are needed in order to provide more support or perhaps even proof of the existence of IGCs. Deep, high-resolution images of the cores of the clusters of galaxies in question need to be taken and studied. This will provide the most stringent test of the IGC model (West *et al.* 1995). Actual observations of IGCs would be ideal, however, a more efficient method to determine the existence of these objects is to model the expected distribution of unresolved objects and compare the models with the data using a distribution test.

A computer program was created in order to efficiently generate models and compare the models with deep images of clusters of galaxies. Initial testing of the program show it to quite effectively find the best-fitting model. More testing is needed, however, in order to establish the feasibility of the program and the range over which it most effectively operates and identify any errors that may exist. The greatest asset of the program is its ability to work with any cluster of galaxies as long as the location of the dynamical center is known and the number of unresolved objects. Then the program needs to be applied to actual deep images of the cores of clusters of galaxies.

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