Supporting Online Material for

Detection of a Large-Scale Structure of Intracluster Globular Clusters in the Virgo Cluster

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Published 11 March 2010 on Science Express
DOI: 10.1126/science.1186496

This PDF file includes:

Methods
Figs. S1 and S2
References
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Methods

Here we briefly describe the methods used to derive the surface number density maps for globular clusters in the Virgo cluster, using the SDSS point source catalog. We used the photometry of the point sources in the SDSS Sixth Data Release (S1) to select globular cluster candidates in Virgo.

The SDSS catalog of point sources in the Virgo direction includes not only the Virgo globular clusters but also the objects that do not belong to the Virgo cluster. There are two types of point sources that are not members of Virgo, which are located in the direction of Virgo: 1) foreground stars belonging to our Galaxy, and 2) unresolved background galaxies. Since we are dealing with relatively bright point sources, the contribution due to the latter is negligible (S2). So we consider only foreground stars.

We need to remove foreground stars and keep only Virgo globular clusters for making a surface number density map for globular clusters. The foreground stars in Virgo are contributed by two types of objects. One is the disk and halo of our Galaxy, and the other is the Virgo overdensity discovered recently in the SDSS (S3). The Virgo overdensity is a large scale substructure covering over 1000 deg² of sky toward Virgo, and is estimated to be located at a distance of 6-20 kilo parsec. It may be a tidal stream or a low-surface brightness dwarf galaxy merging with the Milky Way (S3). Because of the existence of the Virgo overdensity overlapping with our field of interest, the conventional method of using the separate control field at the similar galactic latitude does not work well for subtracting the contribution of these foreground stars. Therefore we adopted a method of using the color magnitude diagram (CMD) for foreground
subtraction as follows.

We selected four fields in the sky to choose appropriate regions in the CMDs for selecting foreground stars and globular clusters in our analysis. (a) The Virgo cluster field: a circular region with radius $R = 6$ deg, centered on M87. This field covers approximately the entire area of the Virgo cluster. (b) The Control field: an annular region with radius $6 < R < 9$ deg, surrounding the Virgo cluster field. This field represents a background field close to the Virgo cluster. It is used for subtracting the contribution of local foreground stars from the Virgo cluster field. (c) Two Reference fields: One circular region (for the Virgo cluster field) and one annular region (for the Control field), both of which are centered at (galactic longitude $l = 80.32$ deg, galactic latitude $b = 74.46$ deg). They are at the same galactic latitude as the Virgo fields, but $\sim 200$ deg distant in galactic longitude from the Virgo fields. They have the same areas as (a) and (b), respectively. These reference fields are used for checking the contribution of general foreground stars in (a) and (b).

Then we constructed raw $i_0 - (g - i)_0$ CMDs for the Virgo cluster field and its reference field, and the Control field and its reference field, as shown in Fig. S1(A), (B), (D), and (E). We subtracted the CMD for the corresponding reference field from the CMDs for the Virgo cluster field and the Control field, displaying the resulting CMDs in Fig. S1(C) and (F).

We used Fig. S1(C) and (F) for choosing the CMD regions to make foreground star maps. Fig. S1(C) includes the contribution of the foreground stars (the Virgo overdensity stars and the remaining disk and halo stars) and the globular clusters in Virgo, while Fig. S1(F) includes the contribution of the foreground stars only. These figures show that the stars in the Virgo overdensity are mostly bluer than the globular clusters. The Virgo overdensity stars contaminate somewhat the bluer side of the blue globular cluster region, while it affects little the red globular cluster region.

We marked the regions for selecting foreground stars (as well as globular clusters) by boxes
in Fig. S1. We chose a bright blue star region (BBS) with the same color range as the blue globular cluster region, and a faint blue star region (FBS) with the same magnitude range as the globular cluster region as in Fig. S1(C) and (F), and used the stars in these regions for creating a blue foreground map to be used for the blue globular clusters. Then we chose a bright red star region (BRS) with the same color range as the red globular cluster region, and a faint red region (FRS) with the similar magnitude range to that of the globular cluster region, and used the stars in these regions for creating a red foreground map to be used for the red globular clusters.

We made the raw surface number density maps for globular cluster candidates (Fig. 2S(A), (D), and (G)) and foreground stars (Fig. 2S(B), (E), and (H)) using the objects inside the above regions in the CMDs. The foreground map was made with a combination of contributions of faint stars and bright stars: \( \sigma(\text{foreground stars}) = (1-a)\sigma(\text{bright stars}) + a\sigma(\text{faint stars}) \), where \( \sigma \) represents the surface number density. The coefficient, \( a \), was determined by minimizing the fluctuation in the difference map for the Control field. Finally we subtracted each of the foreground maps (Fig. 2S(B) and (E)) from each of the raw maps (Fig. 2S(A) and (D)), after scaling the foreground map so that the mean difference for the Control field is zero. Finally we combined the maps for the blue and red globular clusters to make a map for all the globular clusters. The resulting maps are shown in Fig. S2. The final difference maps (Fig. 2S(C), (F), and (I)) show the spatial distribution of all, blue, and red globular clusters in Virgo, respectively.
Figure S1: $i_0 - (g - i)_0$ CMDs for (A) the Virgo cluster field ($R < 6$ deg), (B) the reference field with the same area as the Virgo cluster field (VCF), and (C) the difference between (A) and (B). (D), (E) and (F): similarly for the Control field (CF) ($6 < R < 9$ deg). The boxes represent the boundaries selecting blue globular clusters (BGC), red globular clusters (RGC), bright blue foreground stars (BBS), faint blue foreground stars (FBS), bright red foreground stars (BRS), and faint red foreground stars (FRS). Blue stars in the strong vertical structures in (C) and (F) are mostly Virgo overdensity stars. Darker or redder color represents higher number density.
Figure S2: Surface number density maps for (A) all the point sources with blue globular cluster color, (B) the blue foreground stars, and (C) the difference of these two. (D), (E), and (F): similarly for the red globular clusters. (G), (H), and (I): similarly for all the globular clusters. Large circles represent the boundaries for the Virgo cluster field ($R < 6$ deg) and the Control field ($6 < R < 9$ deg). North is up and east to the left. Redder color represents higher number density.
References and Notes

