

Spatial Correlation Analysis of Globular Cluster Member Stars: Postprint

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Abstract

Taking globular clusters NGC (New General Catalogue) 104, NGC 5139, and NGC 6121 as experimental sample regions, ten stellar parameters including parallax were selected. By introducing spatial analysis theories and corresponding analytical frameworks from geoscience, a geoscience-based research paradigm was proposed for quantitatively describing the spatial distribution characteristics of member stars in globular clusters. The spatial distribution characteristics of each stellar parameter for globular cluster member stars were obtained by calculating global and local Moran indices. Research results indicate that the stellar parameters of member stars in globular clusters NGC 104, NGC 5139, and NGC 6121 exhibit overall spatial positive correlation characteristics, showing spatial agglomeration features, but with differences among different stellar parameters; local spatial distribution also exhibits clustering characteristics, while different member stars show different spatial distribution features and trends. Overall, systematically and quantitatively describing the spatial distribution characteristics of globular cluster member stars using geoscience spatial correlation analysis can provide new insights for globular cluster research.

Full Text

Preamble

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Spatial Correlation Analysis of Globular Cluster Member Stars

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Abstract

This study employs globular clusters NGC 104, NGC 5139, and NGC 6121 as experimental regions and selects ten stellar parameters including parallax. By introducing spatial analysis theories and corresponding analytical frameworks from geography, we propose a geography-based research paradigm to quantitatively characterize the spatial distribution features of globular cluster member stars. Through calculations of global and local Moran's I indices, we obtain the spatial distribution characteristics of various stellar parameters for member stars. The results demonstrate that the stellar parameters of NGC 104, NGC 5139, and NGC 6121 generally exhibit positive spatial autocorrelation, showing spatial clustering characteristics, though significant differences exist among different parameters. The local spatial distribution also reveals clustering patterns, with distinct member stars displaying varied spatial distribution properties and trends. Overall, systematically and quantitatively describing the spatial distribution characteristics of globular cluster member stars through geospatial correlation analysis provides new insights for globular cluster research.

Keywords: globular clusters: individual: NGC 104, NGC 5139, NGC 6121; methods: spatial autocorrelation

As among the oldest known objects in the Milky Way, globular clusters contain far more stars than open clusters, typically comprising 10^5 - 10^7 stars aggregated together. All member stars within a globular cluster are gravitationally bound to the cluster center, orbiting it like satellites while being highly concentrated toward the center, forming a tightly organized spherical structure. The spatial distribution characteristics and underlying mechanisms of globular cluster member stars constitute crucial content for numerous investigations into the formation and evolution of the universe and galaxies, stellar formation and evolution, stellar dynamical properties, and the structure and dynamics of the Milky Way. Studying these spatial distribution features helps reveal clues about stellar evolution and obtain historical information about the Milky Way's evolution, thereby further exploring the laws of galaxy formation and evolution.

With innovations and developments in modern observational technology, the foundational observational data and information sources for globular clusters continue to increase. Current research methods and theories for studying the internal spatial structure and intrinsic mechanisms of globular clusters have become increasingly sophisticated. Scholars have introduced a series of analytical methods including two-point correlation functions, nearest neighbor analysis, percolation, power spectrum analysis, binning analysis (BA) and Kolmogorov-Smirnov (KS) tests, cluster analysis, and multiplicity functions to investigate the spatial distribution structures and characteristics of member stars in globular clusters, yielding fruitful results.

The member stars within globular clusters form unique spatial structures as point-like elements. In the field of geography, scholars have established comprehensive statistical test indicators for spatial autocorrelation of point features, developed specialized computational methods for spatial autocorrelation, and constructed mature theoretical frameworks. Chen Yanguang standardized the mathematical representation of spatial autocorrelation processes based on Moran' s statistic, provided theoretical interpretations of Moran' s index, summarized and developed three computational methods for Moran' s index, and conducted spatial autocorrelation analysis on the total population of towns in Hebi City. Given the similarity between globular cluster member stars and geographical point features, whether we can explore the spatial distribution characteristics of globular cluster member stars from a geographical research paradigm emerges as a novel question derived from previous studies. Currently, the methods for identifying member stars in globular clusters have matured, and many globular clusters contain sufficient numbers of member stars, providing a solid theoretical and data foundation for deeply revealing their spatial distribution characteristics.

As one of the core research directions in geography, spatial autocorrelation is widely applied to quantitatively analyze the degree of association among attribute values of geographical phenomena or spatial entities. Spatial autocorrelation refers to the potential interdependence among observations of certain variables within the same or different distribution regions, commonly used to analyze spatial clustering and variation patterns. Scholars have utilized spatial autocorrelation principles to analyze various geographical phenomena and investigate the clustering and dispersion degrees of geographical elements in different regions. For instance, Ding Yang et al. employed spatial autocorrelation analysis to study the spatial correlation and aggregation of eutrophication levels in Songhua Lake; Yang Zhenqi et al. analyzed the spatial autocorrelation characteristics and influencing factors of soil erosion in small watersheds of exposed arsenic sandstone areas. Beyond geography, spatial autocorrelation theory has been applied to numerous fields including ecology, biology, economics, epidemiology, and criminology, yielding substantial research achievements in studying regular phenomena, spatial distribution patterns, spatiotemporal variation laws, and spatial heterogeneity analysis. Consequently, spatial autocorrelation has become an effective method for testing whether observations of a spatially referenced element are significantly associated with observations at neighboring spatial points, and has interacted with many disciplines. However, this theory has not yet been applied to astronomical research, leaving us lacking knowledge about cluster spatial distribution patterns such as spatial heterogeneity, spatial autocorrelation, and spatial anisotropy—knowledge that plays an irreplaceable role in member star searches and cluster evolution studies.

Based on this, our study selects three globular clusters—NGC 104, NGC 5139, and NGC 6121—as research areas, uses Gaia EDR3 (Gaia Early Data Release 3) as the fundamental data source, and applies geospatial autocorrelation theory to astronomy. By calculating the global Moran' s index, we obtain the spatial

distribution characteristics of stellar parameters for globular cluster member stars, and derive local spatial distribution features based on Moran scatter plots and LISA (Local Indicators of Spatial Association) cluster maps. The theoretical methods of spatial autocorrelation provide approaches and frameworks for studying the spatial distribution characteristics of globular cluster member stars. This research systematically and quantitatively describes these spatial distribution characteristics, offers geographical auxiliary means and a novel entry point for further revealing the underlying mechanisms, deepens our understanding of globular cluster member stars, and opens a new avenue for studying globular cluster spatial distribution features using geographical methods.

2.1 Study Area Overview

NGC 104, NGC 5139, and NGC 6121 are three globular clusters with abundant member stars that are widely used in studies of globular cluster structure and evolution. Detailed information about these clusters is presented in Table 1 .

2.2 Data Sources

A star catalog is a compilation of stellar positions, motions, brightness, and other information at a specific epoch. The Gaia catalog is an essential resource for globular cluster research, released by the European Space Agency' s Gaia space observatory. Gaia EDR3, published in December 2020, contains high-precision data for over 1.8 billion stars and is extensively used in globular cluster structure and evolution studies. Based on the scientific validity of stellar parameters, this study selects ten parameters from the Gaia catalog: parallax, total proper motion (pm), right ascension proper motion component (pmra), declination proper motion component (pmdec), G-band mean magnitude (gm), BP-band mean magnitude (bp), RP-band mean magnitude (rp), color index bp-rp, color index gm-rp, and color index gm-rp, as detailed in Table 2 .

3.1.1 Member Star Selection

The primary task in globular cluster research is accurately identifying member stars, typically accomplished by exploiting differences in physical properties between member stars and field stars. As an ensemble, all member stars of a globular cluster differ from field stars in certain stellar parameters such as brightness, proper motion, and radial velocity. Vasiliev et al. used a mixture modeling approach based on Gaia EDR3 data to identify globular cluster member stars by integrating luminosity and kinematic properties, providing membership probabilities for each star. Consequently, this study adopts the membership probabilities from Vasiliev et al. in the Gaia EDR3 catalog, selecting stars with membership probabilities greater than 0.9 as member stars for each cluster. This yields 7,249 member stars for NGC 104, 6,431 for NGC 5139, and 1,784 for NGC 6121. The spatial distribution of member stars for the three clusters is shown in Figure 1 [Figure 1: see original paper], where the coordinate system is converted from galactic coordinates to a Cartesian system with the

Sun at the origin, the X-axis pointing toward the Galactic center, the Y-axis in the galactic plane perpendicular to the X-axis, and the Z-axis pointing toward the north galactic pole.

3.1.2 Stellar Distance Calculation

Distance is fundamental to spatial correlation analysis. To calculate interstellar distances, positional information must first be obtained. Bailer-Jones et al. employed a probabilistic method to estimate distances to 1.47 billion stars from the Sun based on Gaia EDR3 data. Combined with the galactic longitude and latitude information provided in the Gaia EDR3 catalog, coordinate data for member stars can be derived. Distances between member stars can then be calculated from these coordinates.

3.1.3 Spatial Weight Determination

Spatial weights are essential for spatial autocorrelation analysis. Anselin proposed methods for determining spatial weights, categorizing spatial adjacency relationships into three types: contiguity, distance, and k-nearest neighbors. This study employs a distance-based power decay function to construct the spatial weight matrix, with the specific formulation:

$$W_{ij} = \begin{cases} d_{ij}^{\alpha} & \text{if } i \neq j \\ 0 & \text{if } i = j \end{cases}$$

where W_{ij} is the element in the i -th row and j -th column of the spatial weight matrix, d_{ij} is the Euclidean distance between member star j and member star i (in parsecs), and α is typically set to -2 .

3.2 Spatial Autocorrelation

Spatial autocorrelation analysis can investigate the clustering characteristics of globular clusters. Clustering includes positive and negative correlations: if the trend of a stellar parameter value for a member star matches that of its neighboring member stars, it indicates positive correlation; otherwise, it indicates negative correlation. In spatial autocorrelation, global spatial autocorrelation assesses whether feature values exhibit overall spatial clustering, measured by the global Moran's index, while local spatial autocorrelation identifies clustering types to reveal where clustering occurs, measured by the local Moran's index.

3.2.1 Global Spatial Autocorrelation The global Moran's index measures global spatial autocorrelation, reflecting the degree of aggregation or dispersion of stellar parameter values among member stars. The calculation formula is:

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n W_{ij} \sum_{i=1}^n (x_i - \bar{x})^2}$$

where I represents the global Moran's index, n is the number of member stars, x_i and x_j are the parameter values for member stars i and j , and \bar{x} is the mean parameter value. The value of I ranges from -1 to 1 . When $I > 0$, member star parameter values are positively correlated in space; larger values indicate stronger spatial correlation, meaning high values cluster with high values or low values cluster with low values. When $I < 0$, parameter values are negatively correlated; smaller values indicate greater spatial disparity, meaning low values cluster with high values. When $I = 0$, parameter values are randomly distributed in space.

In spatial autocorrelation analysis, the global Moran's index can be statistically tested using Z-test at a significance level of 0.05. The Z-value is calculated as:

$$Z(I) = \frac{I - E(I)}{\sqrt{Var(I)}}$$

where $E(I)$ is the expected value of I and $Var(I)$ is its variance. When $I < 0$ and $Z(I) < -1.96$, a significant negative correlation exists; when $I > 0$ and $Z(I) > 1.96$, a significant positive spatial correlation exists; when $I = 0$ or $-1.96 \leq Z(I) \leq 1.96$, no spatial correlation exists, indicating a completely random spatial distribution pattern.

3.2.2 Local Spatial Autocorrelation The local spatial autocorrelation index reflects the correlation between a spatial unit's attribute value and the same attribute value in its neighboring units. The local Moran's index is calculated as:

$$I_i = \frac{n(x_i - \bar{x}) \sum_{j=1}^n W_{ij} (x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

where I_i represents the local Moran's index. Like the global index, the local Moran's index requires Z-value interpretation:

$$Z(I_i) = \frac{I_i - E(I_i)}{\sqrt{Var(I_i)}}$$

where $E(I_i)$ is the expected value of I_i and $Var(I_i)$ is its variance. The interpretation of I_i and $Z(I_i)$ values follows the same principles as the global Moran's index.

4 Results and Analysis

4.1 Global Spatial Autocorrelation Results

To investigate the spatial association degrees of different stellar parameters in globular clusters, we calculated global Moran's indices for member stars of NGC 104, NGC 5139, and NGC 6121 using equation (1). The results are presented in Table 3.

The global Moran's index I for all ten stellar parameters across the three clusters is greater than 0, with Z-scores passing the 95% confidence test and P-values all below 0.005 (essentially zero), indicating positive spatial correlation for each parameter. Parallax, representing the angular difference in stellar direction observed from two positions, shows positive correlation because smaller angular differences are observed when member stars are closer together. The proper motions (pm, pmra, pmdec) of member stars also exhibit positive correlation, consistent with the regular kinematic properties of globular cluster member stars. Table 3 reveals that color indices bp-gm and gm-rp have relatively larger global Moran's indices compared to other parameters, demonstrating strong positive correlation. Since color indices represent magnitude differences between different bands that reflect stellar surface temperatures and are closely related to stellar colors, we can infer that when globular cluster member stars are closer in space, their bp-gm and gm-rp values are more similar, indicating more comparable surface temperatures and colors.

4.2 Local Spatial Autocorrelation Results

Processing the data for the three globular clusters yields Moran scatter plots, shown in Figure 2 [Figure 2: see original paper] (using color index gm-rp as an example). In the scatter plot, the horizontal axis represents standardized values of gm-rp, while the vertical axis represents spatial lag values of gm-rp. The first quadrant (High-High, HH) indicates that both the member star and its neighbors have high gm-rp values—higher color indices correspond to lower surface temperatures and redder colors. The second quadrant (Low-High, LH) indicates low gm-rp for the member star but high values for neighbors. The third quadrant (Low-Low, LL) indicates both the member star and neighbors have low gm-rp values—lower color indices correspond to higher surface temperatures and bluer colors. The fourth quadrant (High-Low, HL) indicates high gm-rp for the member star but low values for neighbors. Member stars in HH and LL quadrants show strong positive correlation, while those in LH and HL quadrants show strong negative correlation.

The proportion of member stars in each quadrant of the Moran scatter plots is shown in Figure 3 [Figure 3: see original paper]. The proportions across the ten stellar parameters are similar for NGC 104 and NGC 5139, while NGC 6121 shows noticeable fluctuations compared to the other two clusters, likely because NGC 104 and NGC 5139 have larger member star populations while NGC 6121 has fewer. When a globular cluster contains sufficient member stars,

the quadrant proportions in Moran scatter plots for various stellar parameters may stabilize. Overall, the proportion of member stars falling in HH and LL quadrants exceeds that in LH and HL quadrants for all three clusters, and higher proportions in HH and LL correspond to larger global Moran's indices and more pronounced positive spatial correlation trends.

Quantitative analysis of local correlation degrees for stellar parameters of member stars can be obtained through LISA cluster maps, which include four spatial association types (High-High, Low-High, Low-Low, High-Low) and non-significant (NS) categories. LISA cluster maps at 95% confidence are constructed in Figure 4 [Figure 4: see original paper] (using gm-rp as an example), with proportions of each spatial association type shown in Figure 5 [Figure 5: see original paper].

Figure 5 shows that the High-High type occupies a larger proportion for parameter bp-gm, while the Low-Low type is more prevalent for gm-rp. The Low-High and High-Low types constitute small proportions across all parameters, and the non-significant type appears in all clusters and parameters, consistent with global Moran's index results. Overall, LISA cluster maps exhibit a positive correlation trend, aligning with global spatial autocorrelation results and Moran scatter plot patterns.

4.3 Contributions and Limitations

This study investigates the spatial correlation of globular clusters based on geospatial autocorrelation theory. Distinguishing itself from methods examining cluster grouping and spatial distribution, it re-explores the spatial distribution characteristics of globular cluster member stars from a spatial analysis perspective, introducing spatial analytical methods into globular cluster research. This expands the application scope of spatial autocorrelation theory and provides new approaches for globular cluster studies. Future work will attempt to introduce geostatistical methods to reveal spatial distribution patterns of globular cluster member stars.

Unlike previous astronomical theoretical research, this paper employs geography-based spatial analysis methods to analyze the spatial distribution characteristics and clustering properties of globular clusters. The distinctions from previous studies are summarized as follows:

1. This research examines the spatial distribution characteristics of stellar parameters of globular cluster member stars, whereas modern statistical methods primarily describe member star spatial distributions such as clustering.
2. It introduces geospatial autocorrelation theory into globular cluster research to analyze both global and local spatial autocorrelation features of member stars.

However, this study has several limitations:

1. Based on Gaia EDR3 data, we selected several commonly used stellar parameters. Future research could more fully exploit additional parameter information, particularly stellar mass and age, to further investigate relationship with member star evolutionary stages and facilitate deeper globular cluster studies.
2. While this study confirms the feasibility of applying geospatial autocorrelation theory to globular cluster research, astronomical observational data are continuously updated. With subsequent Gaia data releases offering improved quantity and precision, future studies can utilize the latest Gaia data.

The application value of this research lies in: spatial autocorrelation theory is expected to be widely applied to globular cluster spatial feature studies, and its results can be used for member star searches in globular clusters.

Conclusion

This study utilizes Gaia EDR3 observational data to conduct spatial autocorrelation analysis of globular clusters NGC 104, NGC 5139, and NGC 6121, discussing the spatial distribution characteristics of stellar parameters of their member stars. We adopted the results of Vasiliev et al., using a membership probability threshold of 0.9 as the criterion for member stars in the three clusters. Additionally, we calculated global Moran's indices to obtain global spatial correlations for various stellar parameters of globular cluster member stars, and analyzed local distribution features using Moran scatter plots and LISA cluster maps. Based on this research, we draw the following conclusions:

1. This study represents the first attempt to apply spatial autocorrelation theory to globular cluster research, achieving a description of globular cluster spatial distribution characteristics. The experimental results demonstrate the feasibility of using spatial autocorrelation theory for studying globular cluster spatial autocorrelation features.
2. All ten stellar parameters of globular clusters NGC 104, NGC 5139, and NGC 6121 exhibit positive spatial correlation, with color indices bp-gm and gm-rp showing particularly strong positive correlation. This indicates that member stars in closer proximity tend to have more similar color properties and surface temperatures.
3. The ten stellar parameters of the three globular clusters generally show local spatial clustering characteristics, with higher proportions of member stars in HH and LL quadrants of Moran scatter plots corresponding to more prominent positive spatial correlation.
4. LISA cluster maps overall exhibit positive spatial correlation, with High-High types occupying larger proportions in bp-gm and Low-Low types in gm-rp, consistent with global spatial autocorrelation results.

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