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NGC 2516 OPEN STAR CLUSTER: SIMULATIONS AND MOCK OBSERVATIONS

Abstract

This study examines the NGC 2516 open star cluster using numerical simulations and comparisons with observational data. By employing the phi-GRAPE-GPU code, we reconstructed the cluster's orbit over 123 Myr to identify its birthplace within the Galaxy. Over 70 simulations were conducted, refining the initial parameters of the star cluster to better match present-day observations. The analysis revealed that the standard mass function parameters could not fully replicate the unique characteristics of NGC 2516. To address this, we adjusted the mass function to align more closely with the observed stellar properties. The results demonstrate morphological similarities between the simulated and observed clusters. However, the simulations also include additional tidal tail stars that are absent in observational data, possibly due to observational limitations. These findings highlight the need for more detailed analyses and comparisons. In future studies, we plan to apply machine learning techniques to more accurately identify and classify stars in the tidal tails.

Keywords: NGC 2516, numerical simulations, star clusters, Galactic evolution, mass function.

Introduction

Studying the history of star clusters provides insight into the history of our galaxy. Star clusters form from large molecular clouds [1, 2]. Additionally, open star clusters (OC) are formed in the arms of galaxies. They are young and reside near the galaxy's disk. [3–5].

After the Gaia telescope was activated, it began collecting observational data from both near and distant space, including information on the star clusters (SC) within our Galaxy. Gaia provides highly accurate astrometric data (such as right ascension α, declination δ, proper motion by right ascension , proper motion by declination and parallax π) and photometric data (such as absolute magnitude G and color indices (GBP-GRP)) with minimal error [6].

This data enables the identification of star cluster memberships, which is crucial for understanding the evolution of our Galaxy. In the work, Gaia's data was utilized to determine the membership of stars in various clusters, including NGC 2516 [7].

One of the young open clusters (OCs) of the Milky Way is NGC 2516, also known as Caldwell 96 (or the Sprinter), the cluster situated in the southern sky within the constellation Carina at coordinates α = 119.5270°, δ = −60.8000° [8], and discovered by Abbé Lacaille in 1751–1752 [9]. This cluster lies at a heliocentric distance of X = 26.65 pc, Y = −394.41 pc, and Z = −112.85 pc. It exhibits velocities of U = −21.99 km/s, V = −25.02 km/s, and W = −4.51 km/s. The age of NGC 2516 is 123 Myr, with a mass of M_{cl} = 1973.3M. Its half-mass radius is 7.9 pc, and its tidal radius is 18.3 pc, The cluster contains 2690 members [7].

In this paper, we conduct a tailored simulation of the NGC 2516 cluster by using Phi-GPU code. We identify the birthplace of the cluster within the Galaxy. Subsequently, we determine the initial parameters of the cluster stars for further comparison with observations. All simulations are carried out following a gas expulsion event [10–13].

Materials and Methods

Galactic Context of NGC 2516

We have calculated the cluster's initial position and velocity by performing a backward N-body simulation of its orbit for 123 Myr using the phi-GRAPE-GPU code as in the work [14]. To model the Milky Way, we used a three-component axisymmetric Plummer-Kuzmin potential [15]. Thus, the place of birth and the initial velocities of the cluster were determined. Table 1 presents both the current and initial positions and velocities of NGC 2516 based on observational data. Pang et al. illustrates the locations of all identified members of the 13 target clusters in Galactic coordinates, as shown in Figure 1 [7]. And NGC 2516 has been shown as pink color.

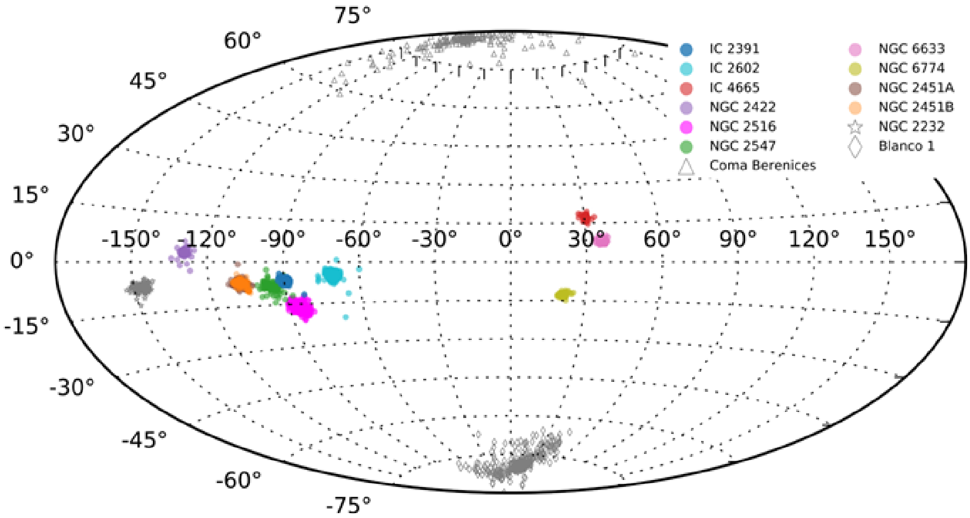

Figure 1 – 2D projection of identified member stars of each target cluster in Galactic coordinates (l, b). Each of the 13 clusters for which the members are obtained via Gaia Early Data Release 3 in study [7]

Table 1 – Current and initial position and velocity of NGC 2516 in Galactocentric cartesian coordinates

Age [Myr]	X [pc]	Y [pc]	Z [pc]	VX [km/s]	VY [km/s]	VZ [km/s]
123	8.1510714 483E+03	-3.94570 41569E+02	-8.95693 80551E+01	-1.52141 11034E+01	2.234854 8042E+02	-5.2921946 487E+00
0	5.74054 50590E+03	5.674317 4345E+03	-5.87520 98540E+01	-1.51544 07861E+02	1.6857979 717E+02	-7.6864457 765E+00

After identifying the cluster's initial birthplace, we proceeded to determine the initial parameters of the selected cluster. Over 70 models of star clusters with varying parameters orbiting NGC 2516 were generated to align with present-day observations [16].

Results and Discussion

To compare the simulation results with the observed data, three types of star distributions were analyzed: the stellar mass distribution, the cumulative distribution of star numbers, and the mass function. Figure 2 illustrates these distributions for the member stars of NGC 2516, as reported by Pang et al. (2021) [7].

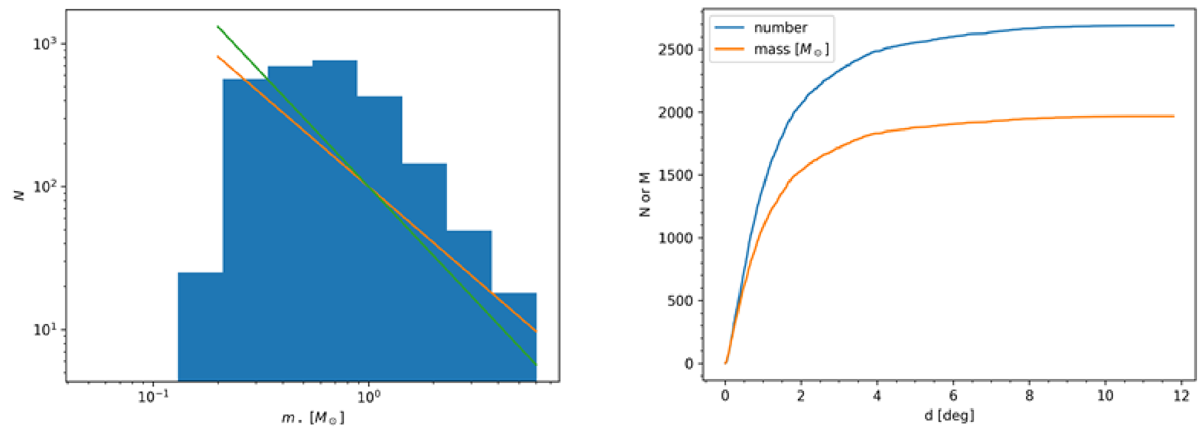

Figure 2 – Mass function and cumulative mass and number distributions of member stars of NGC 2516

The initial mass function (IMF) proposed by Kroupa (2001), which we used in our simulations [13], may not be a good fit for NGC 2516. Our further analysis revealed that NGC 2516 follows a distinct mass function that the Kroupa (2001) IMF cannot replicate [17]. We attempted to adjust the Kroupa IMF to better align with the observations at an age of 123 Myr.

The universal IMF Kroupa [17] has the following form:

$$\xi(m) \propto m^{-\alpha_i} = m^{\gamma_i}, \tag{1}$$

where,

$$\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \leq m/M_\odot < 0.08,$$
$$\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \leq m/M_\odot < 0.50,$$
$$\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \leq m/M_\odot < 1.00,$$
$$\alpha_3 = +2.3 \pm 0.7, \quad 1.00 \leq m/M_\odot,$$

We tried to change values of from equation 1 as well as limits for different The lower and upper limits for initial stellar masses kept the same as in previous simulations our works as [18]:

$$m_{low} = 0.08M_{\odot}, m_{up} = 100M_{\odot}. \tag{2}$$

Our best-matching IMF has the following values for:

$$\alpha_1 = +0.6, \quad 0.08 \leq m/M_{\odot} < 0.75,$$

$$\alpha_1 = +3.1, \quad 0.75 \leq m/M_{\odot} < 100.$$

Figure 3 shows the mass distributions of NGC 2516 (a grey area) and the best-matching simulated cluster (blue lines). The blue dashed line shows the mass distribution of all stars including neutron stars and black holes in the simulation. The blue solid line includes only optically visible stars (about mag for a distance of 400 pc) within the Jacobi radius. In Figure 3 we present the cumulative mass and number distribution profiles. The line colors and styles are the same as in Figure 2. That is the solid line shows optically visible stars that can be observed from the Solar system, while the dashed line corresponds to all simulated stars, including brown dwarfs, white dwarfs, neutron stars, and black holes (if such exists). Comparing the two panels of Figure 3, since the mass difference is smaller than the number of stars, we can understand that the mass excess comes primarily from low-mass stars. Additionally, the simulated cluster also has tidal tails and ex-members that escaped during the violent relaxation, which cannot be included in observational data. That is clear if we compare the proper motions in simulation and observation (Figure 6).

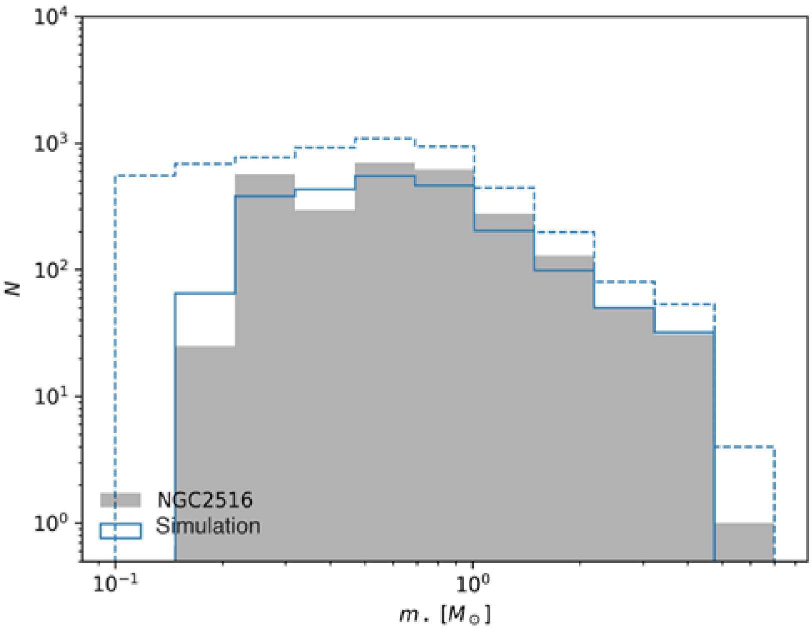

Figure 3 – Stellar mass distributions in NGC 2516 (grey area)
and best-matching simulation (blue).
The dashed line represents all stars, while the solid line corresponds
to the visible stars in the simulations

Using the methods described by Kalambay et al. [19], we produced the mock observational data for our simulations using only the last snapshot corresponding to the age of 123 Myr (Gaia Collaboration 2019 [20]). We present the proper motions in the equatorial coordinates in Figure 5.

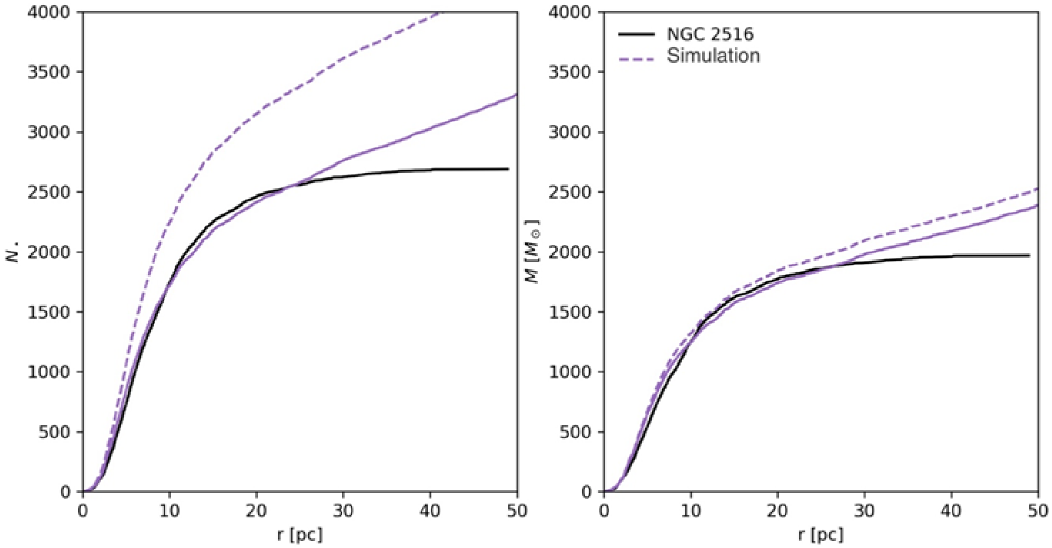

Figure 4 – Cumulative number and mass distribution profiles of a simulated (purple) and actual (black) NGC 2516 star cluster. The dashed line indicates all stars, whereas the solid line represents only the visible stars from the simulations

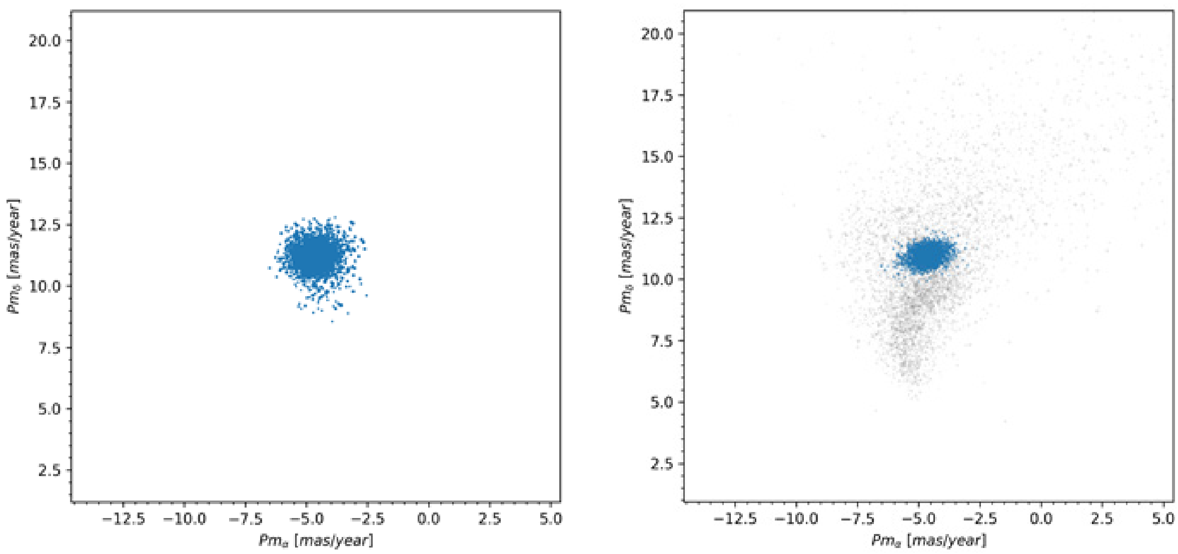

Figure 5 – Proper motions in right ascension and declination of NGC 2516 from observations (left panel) and simulations (right panel)

The actual observational data from [7] is presented in the left panel, while our best-matching simulation is shown in the right panel of Figure 5. The observations have a wider spread of proper motions than the simulation. The positions of optically visible stars (the all-sky view) projected onto the sky are presented in Figure 6, where again, the simulated cluster is in the right panel, while the observed one is in the left.

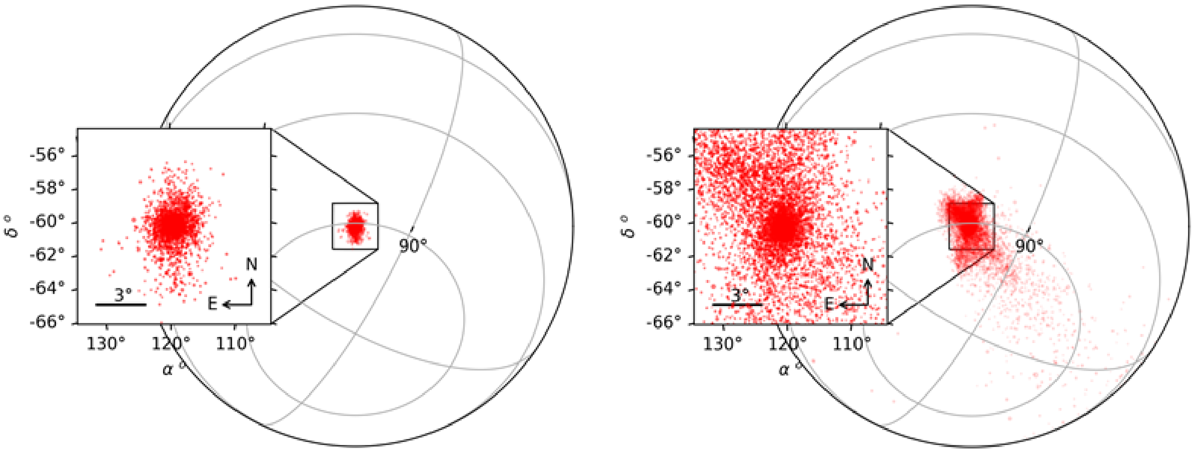

Figure 6 – An all-sky view of NGC 2516 (left) and its tailored simulation (right)

Figure 6 shows that the simulation accurately reproduces the current observed location of the cluster. Additionally, the simulation reveals extra stars surrounding the main cluster, which may have been excluded in observations, possibly being filtered out along with stars from the Galactic field.

Conclusion

The orbit of the NGC 2516 cluster was modeled to determine its birthplace within the Galaxy. Following this, over 70 simulations were conducted to estimate the initial parameters of the star cluster. To achieve this, we analyzed the widely accepted formula for the mass function distribution but found that its standard parameters did not align with observations. Therefore, we adjusted the parameters specifically for our cluster. These revised parameters were subsequently compared to observational data for NGC 2516.

Morphological similarities between the simulation and observations were identified. However, the simulation includes a greater number of stars in the celestial sphere, which may correspond to tail stars that, during observations, could be mistaken for field stars. This discrepancy arises because stars in the tidal tails have distinct motions and can be dispersed around the cluster.

Figures 5 and 6 highlight stars that differ from the main cluster. These findings call for a more detailed investigation and comparison with other studies. In the future, we aim to utilize machine learning techniques to more accurately identify stars in the tidal tails.

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NGC 2516 ШАШЫРАҢҚЫ ЖҰЛДЫЗ ШОҒЫРЫ: МОДЕЛЬДЕУ ЖӘНЕ ЖОРАМАЛ БАҚЫЛАУЛАР

Аңдатпа

Осы жұмыста NGC 2516 шашыраңқы жұлдыз шоғырын сандық модельдеу және бақылау деректерімен салыстыру арқылы зерттеулер жүргізілді. Phi-GRAPE-GPU кодын пайдалана отырып, жұлдыздар шоғырының орбитасы 123 млн жылға кері қарай есептеліп, оның Галактикадағы пайда болған орны анықталды. Бүгінгі бақылауларға сәйкес келетін жұлдыздар шоғырының бастапқы параметрлерін анықтау үшін 70-тен астам модельдеу жүргізілді. Талдау нәтижесінде стандартты масса функциясының параметрлері NGC 2516-ның бірегей сипаттамаларын толығымен көрсете алмайтыны анықталды. Бұл мәселені шешу үшін масса функциясы жұлдыздардың бақыланған қасиеттеріне сәйкестендірілді. Нәтижелер модельдеу мен бақылау арасындағы морфологиялық ұқсастықтарды көрсетті. Дегенмен, модельдеу деректерінде бақылау әдістеріндегі шектеулерге байланысты бақылауларда анықталмаған толысу құйрықтарындағы жұлдыздар табылды. Бұл нәтижелер қосымша талдаулар мен салыстырулардың қажеттілігін көрсетеді. Болашақта толысу құйрығы жұлдыздарын дәлірек анықтау және жіктеу үшін машиналық оқыту әдістерін қолдануды жоспарлап отырмыз.

Тірек сөздер: NGC 2516, сандық модельдеу, жұлдыздар шоғыры, галактиканың эволюциясы, масса функциясы.

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РАССЕЯННОЕ ЗВЕЗДНОЕ СКОПЛЕНИЕ NGC 2516: МОДЕЛИРОВАНИЕ И МНИМЫЕ НАБЛЮДЕНИЯ

Аннотация

В данном исследовании изучается рассеянное звездное скопление NGC 2516 с использованием численных симуляций и сравнений с наблюдательными данными. Используя код phi-GRAPE-GPU, мы восстановили орбиту скопления за последние 123 млн лет, чтобы определить место его рождения в Галактике. Было выполнено более 70 симуляций для уточнения начальных параметров звездного скопления и их приведения в соответствие с современными наблюдениями. Анализ показал, что стандартные параметры функции масс не могут в полной мере отразить уникальные характеристики NGC 2516. В связи с этим мы скорректировали функцию масс для более точного соответствия наблюдаемым звездным свойствам. Результаты демонстрируют морфологические сходства между моделируемыми и наблюдаемыми скоплениями. Однако симуляции также включают дополнительные звезды приливных хвостов, которые отсутствуют в наблюдениях, вероятно, из-за ограничений методов наблюдений. Эти результаты подчеркивают необходимость дальнейших исследований и более глубоких сравнений. В будущих работах мы планируем использовать методы машинного обучения для более точного определения и классификации звезд приливных хвостов.

Ключевые слова: NGC 2516, численные симуляции, звездные скопления, эволюция Галактики, функция масс.

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