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Analytical study of the newly discovered open cluster Gulliver 1

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ABSTRACT

In this work, the astrophysical parameters of the open cluster Gulliver 1 are calculated using Gaia DR2 catalogue. The parameters that covered under this study are the radius, distance, colour excess, age, total mass and relaxation time also the parallax and proper motion values in both coordinates Ra and Dec beside studying the luminosity and mass functions of the cluster. Using the radial density profile, radius is found to be 6.8 ± 0.2 arcmin. We get the distance and age from the colour magnitude diagram to be 2818.38 ± 11 pc and 1.78 Gyr ±20 Myr, respectively. the horizontal-projected distances from the sun on the galactic plane $X_{\odot}$ & $Y_{\odot}$, the distance from the galactic plane $Z_{\odot}$ and the distance from the galactic centre R_{gc} are obtained as 507.5 ± 2 pc, −2222 ± 8.7 pc, −1657.4 ± 6.5 pc and 3609 ± 14 pc respectively. Also, astrometric parameters are obtained such as parallax and proper motions in both coordinates Ra and Dec as 0.31 ± 0.08 mas, −7.9 ± 0.14 mas/yr and 3.6 ± 0.08 mas/yr, respectively. From the estimated relaxation time we inferred that the cluster is relaxed and has a mass of 146.2 $M_{\odot}$. Some parameters are presented for the first time.

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1. Introduction

Clusters of stars are born embedded within giant molecular clouds so that they share a common age and chemical composition (Lada and Lada 2003). So, photometric studies of these clusters give us opportunities to understand star formation processes in the Galaxy which leads to understanding the evolution of the stellar systems, resulted in interactions and dynamical evolution in systems that gravitationally bound (Joshi et al. 2014).

The open cluster Gulliver 1 (RA = 161.582° and DEC = − 57.034°) is discovered by Cantat-Gaudin et al. (2018) while they were observing numerous of known clusters. Some parameters were determined by them such as the radius containing 50% of the cluster, proper motions, parallax and also the corresponding distance. Recently, Bossini et al. (2019) estimated some parameters such as age, distance modulus and extinction for Gulliver 1 beside 268 other clusters. the data that used in their study was extracted from Gaia DR2 and the automated Bayesian tool, BASE-9, was used to fit the Colour Magnitude Diagrams (CMDs), for the most likely member stars, in order to estimate the parameters. Also Hao et al. (2020) re-estimated the astrometric parameters obtained by Cantat-Gaudin et al. (2018) (e.g. radius, members, parallax and proper motions) beside determining the age and extinction in G band.

Gaia DR2 database is the archive that used for data extraction, the most recent information of the ESA space mission. Gaia DR2 is the second release of Gaia after Gaia DR1 where the two archives are based on observations from the same instrument. This GAIA mission was aimed to make the largest, most precise three-dimensional map of the Galaxy. It lunched on December 2013 and planned to end by December 2025. Gaia DR1 was published on September 2016 after 14 months of observations however Gaia DR2 was released on April 2018 after 22 months of observations so Gaia DR2 represent an advance when compared to Gaia DR1, providing new types of data an expanded and improved astrometric and photometric data set. This mission comes after the mission of Hipparcos launched in 1989 by ESA too, for the same purpose, to chart the heavens.

Gaia DR2 contains for more than 1300 million sources in astrometric solutions of coordinates, proper motions in both coordinates right ascension and declination, and parallax within limiting magnitudes of G from 21 to 3 with errors in proper motions are up to 0.06 mas/yr for G < 15 mag, 0.2 mas/yr for G = 17 mag and 1.2 mas/yr for G = 20 mag also the parallax errors are in the range of up to 0.04 mas for sources at G < 15, around 0.1 mas for sources with G = 17 and 0.7 mas at G = 20 at the faint end. And it provides G magnitudes for more than 1700 million sources, with uncertainty from around 0.001 mag at the bright end, G < 13, to around 0.02 mag at G = 20 while the uncertainty of bands G_{BP} and G_{RP} varying from a few milli-mag at G < 13 to around 0.2 mag at G = 20 for

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more than 1380 million sources (Gaia Collaboration, and 625 colleagues 2016; Gaia Collaboration et al. 2018; Evans et al. 2018). Comparison with other catalogues such as, Tycho-2 (Høg et al. 2000), AAVSO Photometric All-Sky Survey (Henden et al. 2015) and SDSS DR12 (Alam et al. 2015), showed that Gaia is usually much better than other catalogues (more details will be found in Evans et al. 2018).

Several methods have been used in star clusters for determining membership probability depended mainly on the kinematic data. Kharchenko et al. (2003) used spatial and kinematic criteria for cluster members selection, where spatial referred to location of a cluster centre and kinematic referred to proper motions. Yadav et al. (2013) used the vector point diagram to specify the membership of the stars in the field of NGC 3766. Dias et al. (2014) presented a catalogue that is contained mean proper motions of stars for optically visible open clusters and also determined the mean proper motions of the clusters and the membership of the stars in the region of each cluster by applying the statistical method. Sampedro et al. (2017) applied three different methods to determine the membership for around 1900 open clusters, first method is described in Sampedro and Alfaro (2016), the second method is called (a Bayesian nonparametric) which developed by Cabrera-Cano and Alfaro (1990). This method is used to determine the members of the clusters using their spatial and the data of proper motions. The third method determined the probabilities of membership only using the stellar proper motions Cabrera-Cano and Alfaro (1985). Maurya and Joshi (2019) identified 350 probable member stars of the cluster NGC 381 using the proper motion of GAIA DR2 as the criterion of membership.

In this work, we aim to re-estimate and calculate the fundamental parameters of the star cluster Gulliver 1 which contribute to grow the stellar formation theories up and understanding structure, and evolution processes of the Milky Way disk. In this respect, the re-estimation of astrometric parameters (radius, distance, parallax and proper motions) and age are provided here beside discussing the luminosity and mass functions. Member stars are obtained counting on proper motions and parallax. Also the horizontal projected distances from the sun on the galactic plane, the distance from the galactic plane and the distance from the galactic centre are obtained, and the total mass, initial mass function and relaxation time are calculated.

The current study is derived as follows: section 2 introduces data extraction. Cluster centre and radius are calculated in section 3 followed by membership determination in section 4. colour magnitude diagram derived in section 5. Luminosity and mass functions are discussed in section 6. Hence, initial mass function and dynamical status are provided in section 7. Finally, conclusion is given in section 8.

2. Data extraction

The data of Gulliver 1 that extracted from Gaia DR2 database[1] contains both photometric and astrometric data beside one of the most important information, the renormalised unit Wight error (RUWE), which give us more details about the observations accuracy (Lindegren 2018). Cantat-Gaudin et al. (2018) and Hao et al. (2020) estimated the radius that containing the half of members as 5.34 and 1.2 arcmins, respectively, so, 10 arc minutes radius around the cluster's centre is used to extract the data within. For more accuracy, some criteria are put to refine the data, e.g. any point source with negative parallax was excluded, maximum uncertainties in parallax and proper motions are chosen which are not exceeded 0.2 mas and 0.3 mas/yr, respectively (Cantat-Gaudin et al. 2018), removing the point sources with RUWE above 1.4 (Lindegren 2018). Using the virtual observatory tool TOPCAT,[2] the vector point diagram is plotted to select the densest area. TOPCAT is preferable because it has some capabilities such as Communicates with external data service bases, easy in dealing with large datasets, perform flexible and fast matching of rows in the same or different tables and has a lot of Plot types (Taylor 2005).

3. Cluster centre and radius

Theoretically, the cluster centre can be defined as the mass centre, or the location where the gravitational potential is largest (Tadross 2009). Observationally, it is the brightest region in the field or the region that contains the major number of the cluster's stars (Littlefair et al. 2003). Here, we can determine the cluster's centre as the location of the highest density of the stars. By applying the Gaussian fitting on the histograms of the right ascension (RA) and declination (DEC), the centres of the Cluster is found as follows RA = 161.596°, DEC = – 57.026 ° as shown in Figure 1.

Also, the radius of Gulliver 1 is resolved as follows, each region is divided into a number of concentric circles, the stars in each shill are counted, and the radial density profile (RDP) is plotted. The King's model (1966) is applied on the RDP, as shown in Figure 2. The cluster's density is represented as:

$$\rho(r) = f_{bg} + \frac{f_0}{1 + (r/r_c)^2} \quad (1)$$

[1]https://gea.esac.esa.int/archive/
[2]http://www.star.bris.ac.uk/~mbt/topcat/

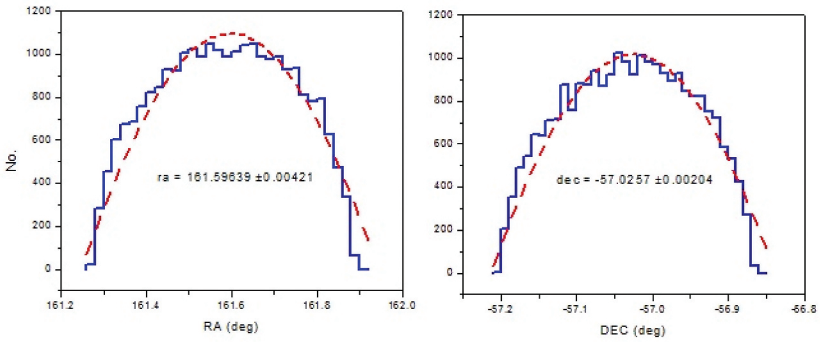

Figure 1. The centre coordinates of Gulliver 1 and the curved dashed red line represents the Gaussian fitting profiles. The values under the curve represent the peaks of the Gaussian curves, which are the centre of the cluster.

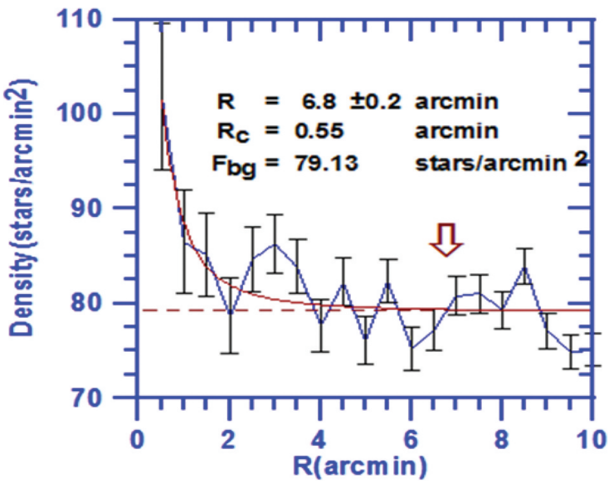

Figure 2. The radial density profile (RDP) of Gulliver 1. The solid red line represents the King fitting (1966). The red dashed line explains the density of the background f_{bg} which is found to be 79.13 stars/arcmin2, core radius r_c is 0.55 arcmin, and border radius r_l is 6.8 ± 0.2 arcmin.

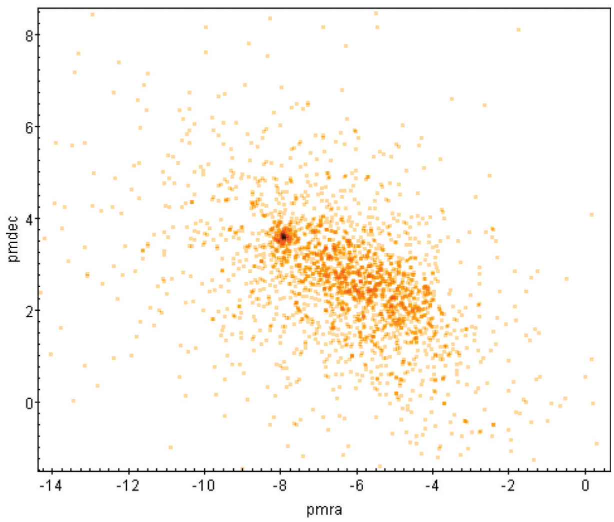

Figure 3. The VPD of open cluster Gulliver 1, it is clear that the dark area shows the concentration of the member stars in that point, which are the most probable cluster members.

where f_{bg} represents the background density, f_0 is the central density, r_c is the core radius. The clusters limiting radius are found to be 6.8 ± 0.2 arcmin, r_c are found to be 0.55 arcmin, and f_{bg} are 79.13 stars/arcmin2.

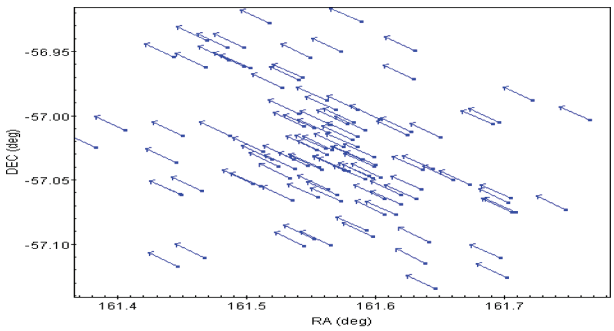

Figure 4. Co-moving stars of Gulliver 1, it shows that the probable member stars have the same directions.

4. Membership determination

One of the most important steps in astrophysical study of an open cluster is to determine the cluster's membership. The popular two methods can be given in photometric and kinematic forms (Ismaiel and Marie 2003). The most common way to identify the cluster stars from field stars based on the data of proper motions and the parallax. In this respect, the vector point diagram (VPD) was drawn, and as expected, there is a dense area was found as shown in Figure 3. The co-moving star vectors is plotted for the cluster, where the real cluster members should have almost the same direction (Tadross 2018) as shown in Figure 4. By applying the previous criteria represented in excludes point sources farther than the radius obtained, have RUWE greater than 1.4, there parallax and proper motion uncertainties larger than 0.2 mas and 0.3 mas/yr, respectively, and finally choosing the highest concentrated area in the VPD, the detected members are found to be 110 stars. Applying the Gaussian fitting, Figure 5, the mean proper motions and parallaxes are determined as follows, pmra = −7.9 ± 0.14 mas/yr, pmdec = 3.6 ± 0.08 mas/yr, and plx = 0.31 ± 0.08 mas.

5. Colour magnitude diagram (CMD)

The CMD is the main important step for determining the astrophysical parameters. It shows that the population of stars in terms of their luminosities and colours. Using the photometric data extracted from Gaia DR2 of the stars of Gulliver 1, the CMD is plotted as shown in Figure 6. This CMD was fitted by the theoretical isochrones of Gaia data, were gained from CMD 3.3.[3] Marigo et al. (2017) isochrones of the present-day Sun metallicity of $Z_{\odot}$ = 0.0152 (Bressan et al. 2013) are used. The results obtained show that, the age of Gulliver 1 is found to be 1.78 Gyr ±20 Myr, distance modulus (m − M) = 12.25 ± 0.2 mag (2818.38 ± 11 pc) and colour excess E (G_{BP} − G_{RP}) = 0.27 mag. Our results are in a good agreement with other literature where Cantat-Gaudin et al. (2018) obtained the distance at 2837 pc, Bossini et al. (2019) estimated the age as 1.47 Gyr and distance modulus as 12.061 mag, and Hao et al. (2020) found the distance of the cluster at 2937.9 ± 21 pc. The wavelengths ratios have been used for correction of the magnitudes for the interstellar reddening and converting the colour excess to E (B − V), where $R_V = A_V/E(B-V) = 3.1; E(B-V) = 0.775E(G_{BP} - G_{RP}) = 0.21$mag (Cardelli et al. 1989 & O'Donnell 1994).

Correspondingly, from the galactic coordinates of Gulliver 1 (b = 286.5136 deg and l = +01.7953 deg), we used Equations (2) to estimate the projection distances $X_{\odot}$ & $Y_{\odot}$, the distance from the galactic plane $Z_{\odot}$, and the distances from the galactic centre R_{gc} (Tadross 2011) and they are found to be 507.5 ± 2 pc, −2222 ± 8.7 pc, −1657.4 ± 6.5 pc and 3609 ± 14 pc respectively.

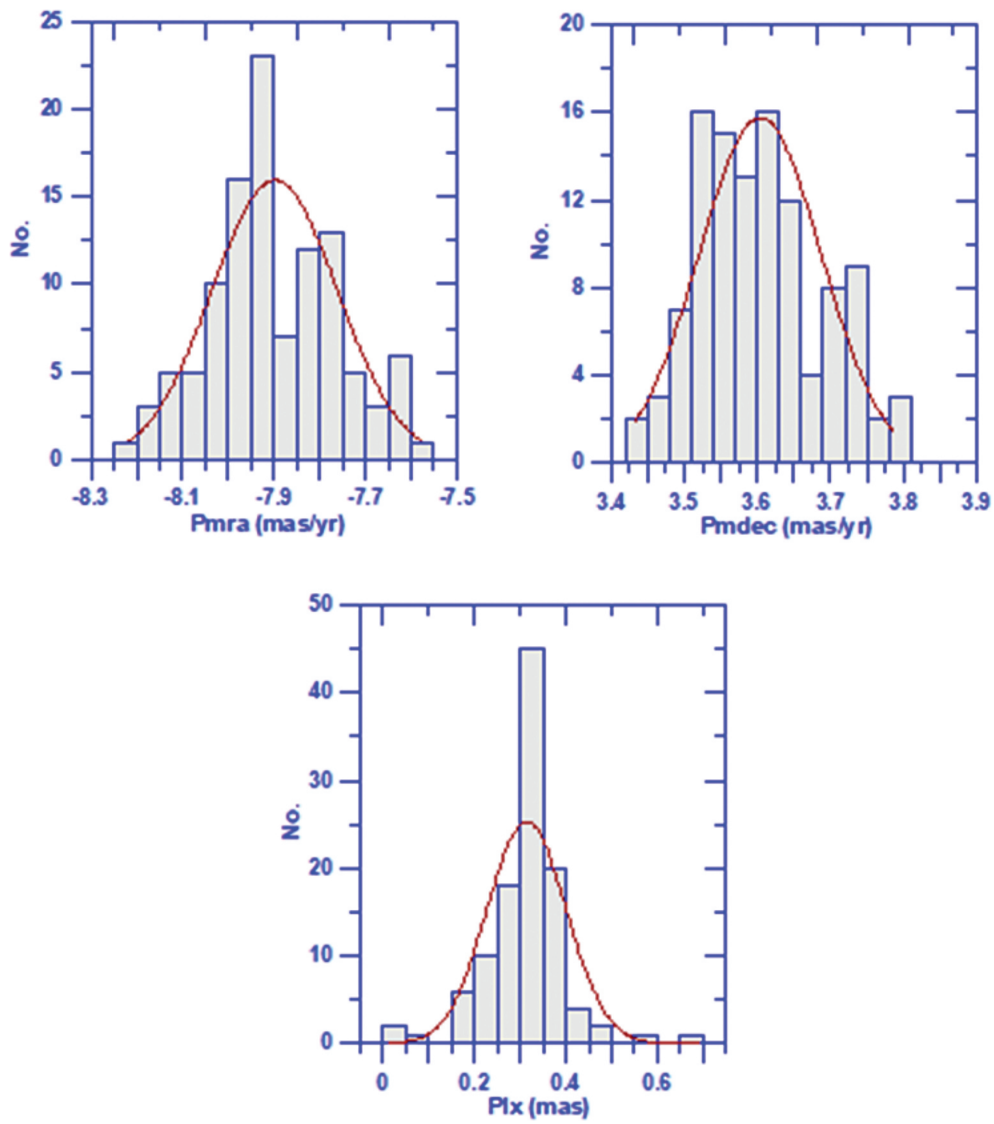

Figure 5. The determination of mean proper motion in RA, DEC and parallax from left to right, up to down respectively, where the red line shows the Gaussian fitting.

[3]http://st.oapd.inaf.it/cgi-bin/cmd

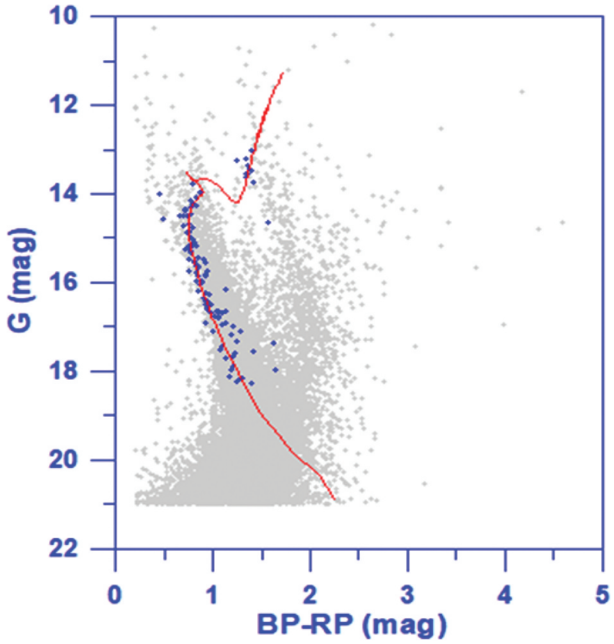

Figure 6. CMD of Gulliver 1, it shows the field stars in grey, member stars in blue and this red line shows the theoretical isochrone with age of 1.78 Gy.

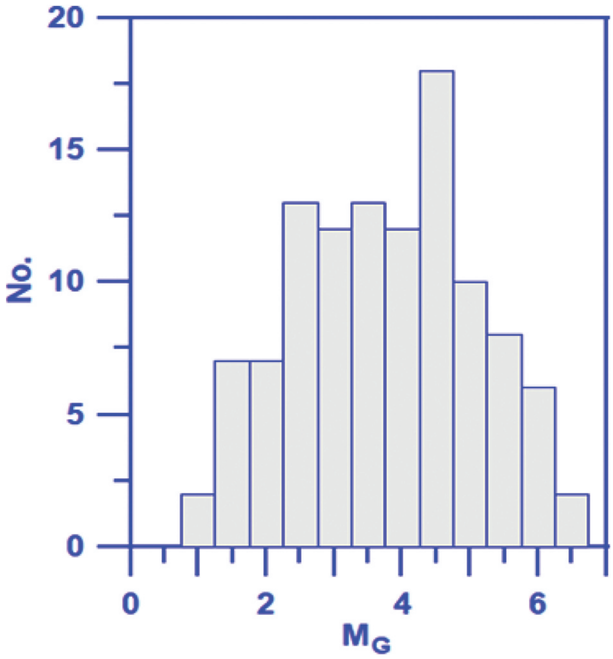

Figure 7. The LF of Gulliver 1 with interval bins 0.5 mag.

$$X_\odot = d\cos b\cos l$$
$$Y_\odot = d\cos b\sin l$$
$$Z_\odot = d\sin b \quad (2)$$
$$R_{gc} = \left((d - X_\odot)^2 + {Y_\odot}^2 + {Z_\odot}^2\right)^{1/2}$$

Where d is the distance to the sun in parsecs.

6. Luminosity and mass functions

Luminosity function (LF) is the distribution of the absolute magnitude of the member stars of the cluster. The member stars are calculated with regard to the absolute magnitude M_G after applying the distance modulus obtained above. The histogram is drawn with interval bin $\Delta M_G = 0.5$ mag. Figure 7 shows the luminosity function of Gulliver 1. To obtain the masses of the member stars, the polynomial equation constructed from the data of the fitted suitable theoretical isochrones of Marigo et al. (2017) is estimated (Equation (3)), which is called mass–luminosity relation Figure 8.

$$Mass = 1.861 + 0.033M_G - 0.111M_G^2 + 0.018M_G^3 - 0.001M_G^4 \quad (3)$$

Where M_G is the absolute magnitude of the member after applying the distance modulus on the apparent magnitude. Then, we can get the mass of each star by Substituting the luminosity by the corresponding absolute magnitude in this equation. The obtained masses are divided into bins and counting the number of stars in each mass bin to calculate the total mass of the cluster by summing the stellar masses in all bins which were found to be 146.2 $M_\odot$.

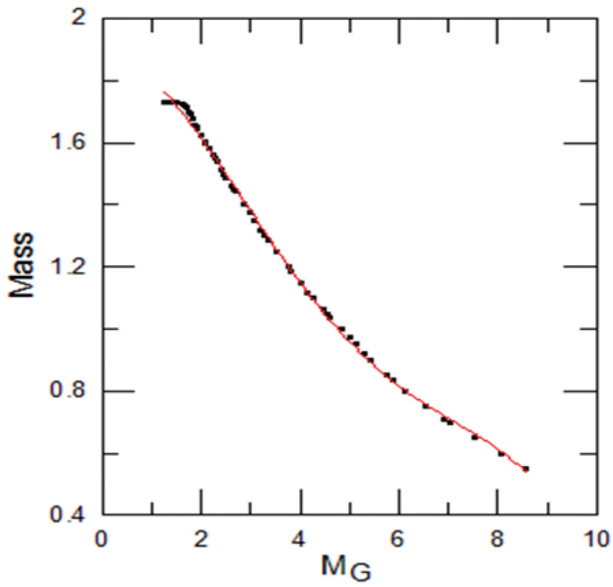

Figure 8. The mass – luminosity relation of Gulliver 1, and the red line represents the polynomial 4th degree fitting.

7. Initial mass function & dynamical status

Initial mass function (IMF) of the cluster's stars is fundamental and essential ingredients in models of galaxy formation and stellar evolution. It might be derived by applying the linear fitting on the histogram of masses of the member stars. In other words, determining the slope of the mass distribution of cluster members (Tadross 2018) can be expressed in terms of the star's numbers dN/dM in mass range from M

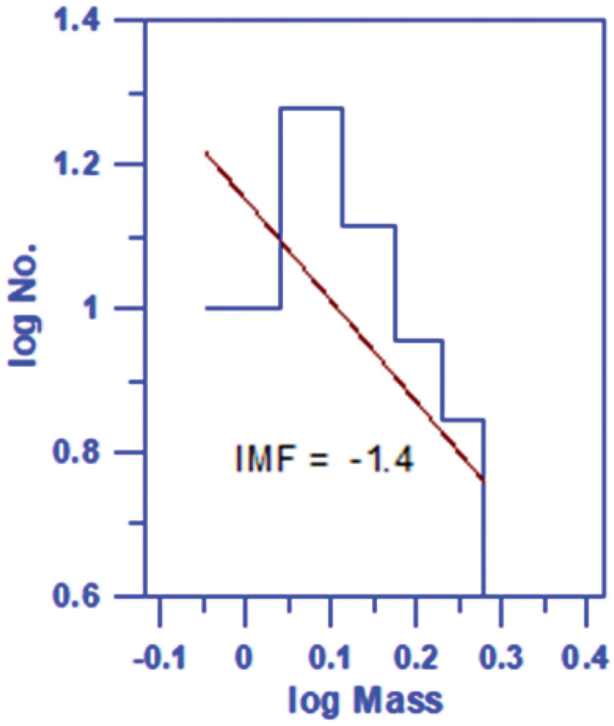

Figure 9. The IMF of Gulliver 1, with a value agree with.Kroupa (2001) and Salpeter (1955)

to$(M + dM)$, and dimensionless exponent α as follows:

$$\frac{dN}{dM} \propto M^{\alpha} \tag{4}$$

The results are found to be −1.4, as shown in Figure 9. This value tell us that the distribution of the masses in range of $0.08 \le m/M_{\odot} < 0.50$ (Salpeter 1955& Kroupa 2001)

The relaxation time is the time scale on which a cluster will lose all traces of its initial conditions (Bisht et al 2018). It is the important parameter that confirms if the cluster is already relaxed or still under formation processes. It can be explained by the relation of Spitzer and Hart (1971) as follows:

$$T_R = \frac{8.9 \times 10^5 \sqrt{N} \times R_h^{1.5}}{\sqrt{>} \times \log(0.4N)} \tag{5}$$

Where the cluster members number is represented by N, ‹ m › is the average mass of the cluster's members in solar unit, and R_h represents the radius containing half of the cluster mass in parsecs. By assuming the R_h equals half of the cluster radius. Then, by applying Equation (5), the relaxation time is found to be 31.15 Myr. This value is smaller than the estimated age obtained from the CMD, which means that the cluster is dynamically relaxed.

8. Conclusion

We presented here re-estimation and calculation for the fundamental parameters of the open star cluster Gulliver 1. Some parameters are obtained previously by Cantat-Gaudin et al. (2018), Bossini et al. (2019) and Hao et al. (2020). The data are extracted from Gaia DR2 catalogue and refined under some criteria for example the renormalised unit weight error is taken in our consideration. The selection of member stars is based mainly on the Gaia proper motions. Some parameters are calculated for the first time such as the horizontal-projected distances from the sun on the galactic plane, the distance from the galactic plane, the distance from the galactic centre, total mass, initial mass function and relaxation time. From the age and value of the IMF (−1.4) we concluded that Gulliver 1 is an intermediate-aged cluster and the mass distribution in the range between 0.08 and 0.50 $M_{\odot}$. Also, we inferred that the cluster is relaxed when compare the relaxation time by the estimated age. Our results are compared with the literatures (e.g. Cantat-Gaudin et al. 2018; Bossini et al. 2019; Hao et al. 2020) and summarised in Table 1.

Table 1. The comparison between results of open cluster Gulliver 1 with the literatures, where R_{50} is the radius containing 50% of the cluster members.

Parameter	Present work	Cantat-Gaudin et al. (2018)	Bossini et al. (2019)	Hao et al. (2020)
R (degree)	0.113 ± 0.003	R_{50} = 0.089	- -	R_{50} = 0.02
Members	110	107	- -	- -
Distance (pc)	2818.38 ± 11	2837.3	2583.44	2937.9 ± 21.7
$\bar{\mu}_x$ (mas yr^{-1})	−7.9 ± 0.14	−7.926 ± 0.076	- -	−7.83 ± 0.05
$\bar{\mu}_y$ (mas yr^{-1})	3.6 ± 0.08	3.582 ± 0.081	- -	3.63 ± 0.03
Parallax (mas)	0.31 ± 0.08	0.323 ± 0.037	- -	0.34 ± 0.01
E(B-V) (mag)	0.295	– –	- -	- -
Age (Gyr)	1.78 ± 20 Myr	– –	1.42	- -
Distance modulus (mag)	12.25 ± 0.2	– –	12.061	- -
X (pc)	507.5 ± 2	– –	– –	– –
Y (pc)	−2222 ± 8.7	– –	– –	– –
Z (pc)	−1657.4 ± 6.5	– –	– –	– –
R_{gc} (pc)	3609 ± 14	– –	– –	– –
Total mass (M)	146.2	– –	- -	- -
IMF	−1.4	– –	- -	- -
Relaxation time (Myr)	31.15	– –	- -	- -

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Disclosure statement

No potential conflict of interest was reported by the authors.

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