# An astrometric and photometric study of the young open cluster NGC 2168 and its possible member, the eclipsing binary [NBN2015]77

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## Abstract

We present an astrometric and photometric study of the young open star cluster NGC 2168 and its proposed member

## Introduction

Eclipsing binaries in star clusters an ideal test for the theories of binary structure and evolution. NGC 2168, also known as Messier 35 (M35), is an important young, nearby, and large open cluster of stars in the northern constellation of Gemini (Bouy et al. 2015). [NBN2015] 77, also known as 2MASS J06092929+2407028, is a poorly studied eclipsing binary star, which is located in the field of the well-known open cluster NGC 2168. It is a short period (0.397219$^d$) eclipsing binary system as defined by Nardiello et al. (2015).

## Data

For open cluster NGC 2168, we used both the GAIA DR2 and the 2MASS databases to obtain the photometric and astrometric measurements. The Gaia DR2 picks up more than 1.3 billion sources in three photometric bands (G, $G_{BP}$ , $G_{RP}$), also the proper motion and parallax (Gaia Collaboration et al. 2018; Lindegren et al. 2018). The G-band magnitude limit of Gaia DR2 data is 21 mag, while the magnitude limits of 2MASS in H (1.650 μm), J (1.250 μm), and K (2.170 μm) are 15.100, 15.800, and 14.300 mags respectively. We also used the optical data from Nardiello et al. (2015) to obtain [V_(B-V] Color Magnitude Diagram and the photometric analysis of [NBN2015] 77 . Nardiello et al. (2015) data obtained by using the Astronomical Observatory of Padova, by using the SBIG STL-11000M camera, attached to the Asiago 67/92 cm Schmidt Telescope (Nardiello et al. 2015). The photometric V, B and R data were collected over three seasons.

## References

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## NGC 2168 Data Reduction and Analysis

1. We extracted the data for the studied cluster, centered on the coordinates of the Cluster NGC 2168 in J2000 (RA=06:08:54, DE=+24:20:00), ℓ = 186°.591 and b = +2°.191 (Dias et al. 2002) in the Virtual Observatory tool TOPCAT (Taylor 2005), within a radius of 15 arcminutes. After that we cross-matched between Gaia DR2 and 2MASS data, the number of stars was 5569.
2. The best astrometric precision for the proper motions is obtained using the sources with three conditions:$G \leqslant 18$ , uncertainties of less than 0.3 mas/yr in proper motions and 0.15 mas in parallax (Lindegren et al. 2018; Cantat-Gaudin et al. 2018).
3. Using our membership criteria depend on the chosen overdensity region (cluster region) from the VPD (Fig. 1), which is a compromise between field stars and the cluster members (see Bisht et al. 2019). The stars are considered members if they lie inside the overdensity cluster region in the VPD and proper motions in RA and DE within from the mean proper motion and they must have a clear main sequence of CMD (Fig. 1). These stars must be inside the limiting radii and have the same direction of proper motion vectors. The cluster members have the same angular speed in space.We estimated the mean proper motion of NGC 2168 to be $pmRA = 2.293 \pm 0.198$ and $pmDE = -3.423 \pm 0.575$ (Fig. 2)..
4. The direction of the proper motion vector of the eclipsing binary [NBN2015] 77 in (Fig. 3) is different from the direction of the star members. So it doesn't seemto be a member, despite its position close to the isochrones of the color-magnitude diagrams in optical and 2MASS (Fig. 6).
5. the center of the cluster is estimated using the Gaussian fitting at a value of the maximum stellar density of the cluster's area. The center of the open cluster NGC 2168 is obtained at $RA = 92^\circ.228 \pm 0.052$ and $DE = +24^\circ.330 \pm 0.043$,hence, the Galactic coordinates are ℓ=186°.596 and b= +2°.192 (Fig. 4).
6. To calculate the core and the limiting radii, we have established the Radial Density Profile (RDP) for the open cluster NGC2168.Using King's model (1966) the best fit of the radial density profile of NGC 2168 has been performed and shown in (Fig. 5). we have determined $f_0 = 33.2\ star/arcmin^2$and $R_{cor}$ = 0.44'. The open cluster NGC 2168 has the limiting radii as $R_{lim}$ = 8'.
7. Using multi-color magnitude diagrams (Gaia DR2, optical BV, 2MASS), we determined the age,color excess, and distance of NGC 2168 to be 126 Myr,0.290 ± 0.049 mag, 862.349±67.497 pc respectively, see Fig. 6.

## [NBN2 015]77 Data Reduction and Analysis

1. Using the method of Kwee&Woerden (1956),we calculated the new ephemeris for the system as follows :
$$HJD\ (MinI) = 2456639.120\ (\pm 0.001) + 0.397219^d \times E$$
2. The light curve analysis of the system [NBN2015]77 was carried out using the updated version of the Wilson– Devinney code (Nelson (2009)). As there are no available spectroscopic observations for the system, we estimated the mass ratio (q = M2/M1) value for the system using the "q-search" method, (Fig. 7) shows the converged q reached at the value of 0.242.
3. The light curve analysis for the V and R bands of the system [NBN2015]77 was performed using the program of Wilson-Devinney (W-D, Nelson 2009; Wilson and Devinney 1971). Fig. 8 shows the best match between the model and the observed light curves, while Table 1 presents The orbital parameters for both V and R light curves. The analysis of the light curves shows that the primary component is the massive and hotter one with a difference in effective temperature = 111 K. According to the accepted solution, the system [NBN2015] 77 is consisting of two components with spectral type K0 and K1 respectively, following Covey (2007).
4. Using the empirical relation adopted by Torres (2010), we calculated the absolute physical parameters (e.g.M, R) of the two components of [NBN2015] 77.

## Conclusion

- The membership is investigated using a criterion based on the high-precision Gaia proper motions. We found 187 member stars in Gaia, 2MASS, and the BV catalog of Nardiello et al. (2015).176 of them are in the catalog of Cantat-Gaudin et al. (2018) with a high membership probability, larger than 70%.
- The eclipsing binary[NBN2015] 77 has very high relative Gaia parallax uncertainties.Bailer-Jones et al. (2018) obtained its distance as $d_{EB}(Bailer) = 2972\ pc$ , comparing this value with the cluster mean distance of $d_\odot = 862.349 \pm 67.497\ pc$ indicates that the eclipsing binary [NBN2015] 77 is more probably lying in the background as a field star.
- The positions of both components of [NBN2015] 77 on the evolutionary tracks ZAMS and TAMS computed by Mowlavi et al. (2012), reveal that the secondary component, in the mass-radius and mass-luminosty relations, is an evolved one while the primary component is amean sequence star fig. 9.

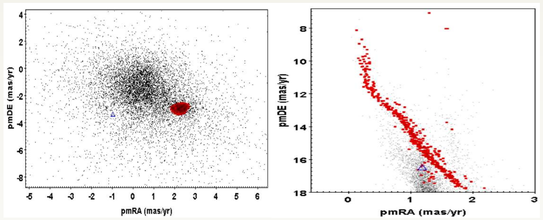


Fig. 1: The left panel shows the Vector Point Diagram (VPD), and the right panel shows the Color Magnitude Diagram (CMD) of the open cluster NGC 2168. The selected red region from the VPD marks the candidate member stars. The blue triangle and the black dots represent the eclipsing binary [NBN2015]77 and the field stars respectively. The red dots on the CMD represent candidate members.

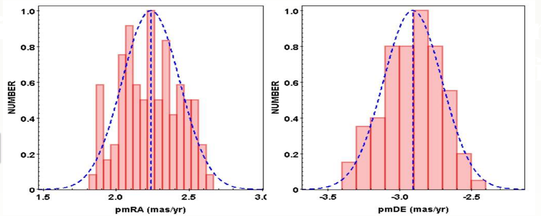


Fig. 2: The histograms of the proper motion in RA (mas/yr) and DEC (mas/yr), and the Gaussian fits are shown in blue dashed lines.

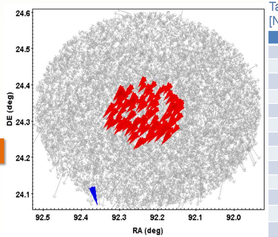


Fig. 3: Projection on the sky of the proper motion vectors. The red vectors (red triangles) represent the cluster members, the blue vector (blue triangle) represents the eclipsing binary [NBN2015]77 and the gray vectors (gray arrows) represent the field stars.

Table 1: THE ORBITAL SOLUTION FOR [NBN2015]77 IN V AND R BANDS.

| Parameter | R | V |
|---|---|---|
| Λ | 7000 Å | 5500 Å |
| T1(K) | 5191 | 5191 |
| T2 (K) | 5080 ± 43.870 | 5080±69.500 |
| Q | 0.242±0.009 | 0.242±0.018 |
| Ω1=Ω2 | 2.239±0.022 | 2.239±0.048 |
| g1=g2 | 0.320 | 0.320 |
| A1=A2 | 0.500 | 0.500 |
| X1=X2 | 0.647±0.040 | 0.647±0.035 |
| Y1=Y2 | 0.16 | 0.16 |
| i(◦) | 68.9±0.955 | 68.9±1.840 |
| r pole1 | 0.495 | 0.495 |
| r side1 | 0.543 | 0.543 |
| r back1 | 0.574 | 0.574 |
| r pole2 | 0.271 | 0.271 |
| r side2 | 0.286 | 0.286 |
| r back2 | 0.349 | 0.349 |
| L1/(1+l2) | 0.785±0.092 | 0.789±0.279 |
| ∑(o-c)$^2$ | 0.011 | 0.018 |

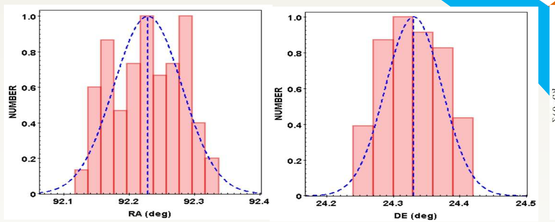


Fig. 4: Inferring the center of NGC 2168 in RA (left panel) and DE (right panel). The blue lines are Gaussian fits.

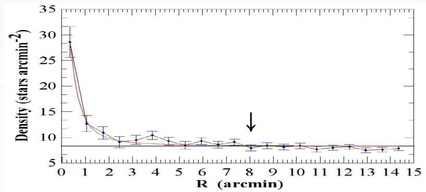


Fig. 5: The radial density profile of NGC 2168. The red curved line is our bestfit King profile). The value of the limiting radius is $R_{lim}$ = 8'. The solid line represents the background density.

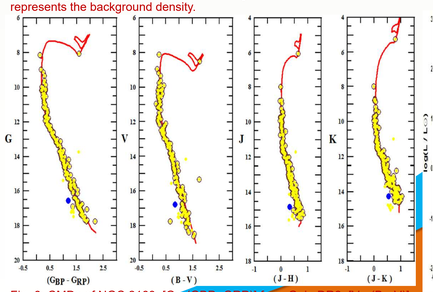


Fig. 6: CMDs of NGC 2168: [G - (GBP- GRP)] from Gaia DR2, [V - (B - V)] from Nardiello et al. (2015) and [J - (J - H) & J - (J - K)] from 2MASS data respectively. The blue circles in the CMDs refer to the position of the eclipsing binary [NBN2015]77. The yellowcircles represent 187 member stars in the optical (Gaia & [V - (B - V)]), and the 2MASS data using our criteria. The brown open circles represent 176membesr stars obtained by Cantat-Gaudin et al. (2018) using their UPMASK code to determine membership probabilitieslarger than 70%.

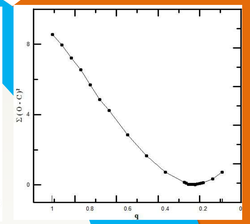


Fig. 7: q - ∑ (O – C)² relation for [NBN2015] 77

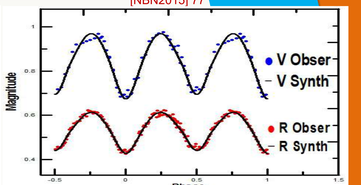


Fig. 8: V, R band data for the system [NBN2015]77, as fitted with the synthetic model (sold line)

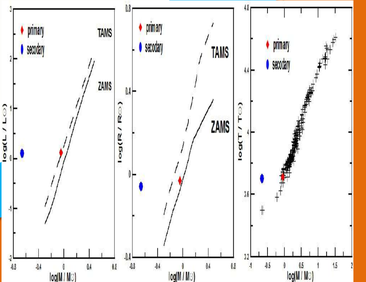


Fig. 9: The position of the components of the system on the Mass-Luminosity (left), Mass-Radius (middle) and empirical M - Teffrelation (right) for intermediate mass stars.