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The Young Open Cluster NGC 1981

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Abstract. An stellar cluster is a gravitationally bound group of stars that present a common origin, so that its members have similar age, kinematics and chemical composition. The study of young clusters help to constrain the formation and evolution models as well as the Galatic disc properties. Open clusters in the embedded phase form at a rate that exceeds by more than an order of magnitude the forming rate of optically visible clusters, indicating that these young systems have a very low chance of survival. NGC 1981 is a young cluster, located 1° north of the Orion Nebula in the Galactic coordinates (l,b) = (208.9, -18.98). Although NGC 1981 is in a region of intense star formation, with several clouds of gas and dust, it presently inhabits a relatively dust-free field, perhaps as a consequence of its own evolution. Aiming to better understand the star formation in Orion, we have studied NGC 1981, which has been classified with two conflicting ages (30 and 5 Myrs). GAIA DR2 and EDR3 photometry and astrometry, medium resolution spectroscopy collected at CASLEO and OPD, have been analysed with our astrometric decontamination method and together with the radial velocity of the cluster members to dertermine, with better precision, the astrophysical parameters of NGC 1981 and its neighbour cluster NGC 1977, which is contaminating spatially and astrometrically NGC 1981. Our analysis has revealed that NGC 1981 and NGC 1977 are indeed young, 8 Myrs and 4 Myrs old, respectively. These findings reinforce the scenario of sequential star formation in the Orion Nebula. The dispersion in the astrometric data of its members, suggest that NGC 1981 may be going through some disruptive processes and it is not expected to survive by more than a few million years.

Resumo. Aglomerados estelares são um grupo de estrelas ligados gravitacionalmente, que apresentam uma origem em comum, portanto possuem idade, cinemática e composição química similares. O estudo de aglomerados jovens impõe restrições aos modelos de formação e evolução estelar, assim como às propriedades do disco da Galáxia. Aglomerados abertos na fase embebida se formam a uma taxa que excede por uma ordem de grandeza a de aglomerados opticamente visíveis, indicando um índice elevado de destruição desses sistemas jovens. NGC 1981 é um aglomerado jovem, localizado 1° ao norte da Nebulosa de Órion nas coordenadas Galácticas (l, b) = (208.09, -18.98). Embora NGC 1981 esteja em uma região de intensa formação estelar, com muitas nuvens de gás e poeira, ele atualmente habita um campo relativamente livre de poeira, talvez como consequência da sua própria evolução. Buscando entender melhor o cenário de formação estelar na região da Nebulosa de Órion, estudamos NGC 1981, que têm sido classificado com duas idades conflitantes (30 e 5 Manos). Dados de fotometria e astrometria do DR2 e do EDR3 da missão GAIA, espectros de média resolução obtidos no CASLEO e no OPD, foram analisados com o método de descontaminação astrométrica desenvolvida pelo nosso grupo e a velocidade radial das estrelas membro, para determinar com maior precisão os parâmetros astrofísicos de NGC 1981 e do aglomerado vizinho NGC 1977, que está contaminando espacialmente e astrometricamente a região de NGC 1981. Confirmamos a juventude de NGC 1981 (8 Manos), que junto com a idade de NGC 1977 (4 Manos), dão suporte ao cenário de formação estelar sequencial na Nebulosa de Órion. A dispersão nos dados astrométricos das estrelas membro sugere que NGC 1981 esteja passando por um processo disruptivo e não se espera que ele sobreviva mais do que alguns milhões de anos.

Keywords. (*Galaxy*): open clusters and associations: individual: NGC 1981 – (*Galaxy*): open clusters and associations: individual: NGC 1977 – Stars: evolution – Stars: kinematics and dynamics

1. Introduction

Open clusters (OCs) belonging to star-forming complexes are the leftovers of the initial stellar generations. The study of these young systems provides constraints to models of star formation and evolution as well as to the properties of the Galactic disc (Jacobson et al. 2016; Cantat-Gaudin et al. 2018; Liu & Pang 2019; Ferreira et al. 2020; Holanda et al. 2021). Young OCs can be found in distinct evolutionary phases, like the embedded phase, when the cluster is still surrounded by its progenitor cloud, and the gas-free phase, when the stellar evolution of the cluster's content has already dispersed it. Due to the disruptive effects that occur from the feedback of the first generation of the cluster's stars as well as due to tidal shocks on the young stellar cluster, by the surrounding gas cloud from the natal environment, only about 7 percent of the OCs survive the embedded phase (Lada & Lada 2003; Kruijssen et al. 2014).

NGC 1981 is a young sparse cluster located 1° north from the Orion Nebula. Although NGC 1981 is in a region of intense star formation, it presently inhabits a relatively dust-free field, perhaps as a consequence of the cluster evolution as its massive stellar content may have contributed to the energy release into the interstellar medium (ISM), either by means of supernovae and/or stellar winds. Additionally, a fraction of the cluster low-mass stars may have evaporated from the region in its early evolution leading to the present sparse, loose structure (Maia, Corradi, & Santos 2010) (hereafter MAIA10).

NGC 1981 is part of the Orion OB1 association, subgroup c, which is 26 Myr old and located closer to us (~ 400 pc) than the younger Orion Nebula by at least 10 pc (Bally 2008). This division in subgroups is questioned in favour of a continuous star-forming event (Muench et al. 2008). Since NGC 1981 bright stars are early B-types, a plausible evolutionary sequence would entail supernovae explosions from O-type progenitors causing the compression of the ISM and formation of the younger populations.

Investigating the hierarchical star formation through the spatial distribution and the cluster's kinematic, Elias, Alfaro, & Cabrera-Caño (2009) classified NGC 1981 as a bound cluster, taking into account the age of 30 Myrs, as determined by Kharchenko et al. (2005). This age determination is much older than the others nearby clusters, as NGC 1977, which is located few degrees below in declination, with an age between 2 - 4 Myrs (Kim et al. 2017) and, further below, M42 with less than 1 Myr (Pabst et al. 2020).

Employing near-IR 2MASS photometric data, MAIA10 calculated the cluster centre at (RA, DEC) = (05^h 35^m 08^s, -04° 20′ 35″), the structural parameters from King-profile fittings obtaining a core radius R_c = (0.09 ± 0.04) pc and central density σ_o = 200 stars/pc^2. A limiting radius of R_{lim} = (1.21 ± 0.11) pc was derived from the Radial Density Profile (RDP).

They also devised a method that accounts for the field contamination based on Bonatto & Bica (2007) to statistically remove the underlying field population from the cluster CMD by using an offset field to sample the background contamination, and allow to derive the photometric memberships. Tested on NGC 1981 with multiple offset fields, the procedure reliably presented an average field-star exclusion efficiency of 84 percent, separating cluster members with an average deviation of 5 percent in the number of stars and 6 percent uncertainty in the photometric memberships.

By using optical B V R_c I_c data obtaing at SOAR alongside 2MASS data, MAIA10 also performed an isochrone fitting on the decontaminated data and determined values of E(B-V) = (0.07 ± 0.03) mag, $(m - M)_o$ = (380 ± 17) pc, t = (5 ± 1) Myr. Mass functions (MFs) were computed for stars inside the cluster limiting radius and total mass estimated from them. They derived MFs for stars inside the inner 5.5' and 11' and evaluated the total mass inside these regions: m = (30 ± 6) $M_\odot$ and m = (107 ± 13) $M_\odot$, respectively.

The absence of evolved sequences in cluster CMDs makes the determination of its age unreliable if standard models are used, without Pre-Main-Sequence (PMS) stars. The PMS isochrone fitting suggest that stars with ages = [1, 10] Myr coexist in NGC 1981 and that most of the high-membership (P > 0.6) stars seem to fall between the young isochrones of 1 and 5 Myr. It was shown that this population of faint PMS stars is related to the cluster itself rather than the nearby Orion Nebula Cluster (MAIA10).

Alves & Bouy (2012) found a large population of young stars in front of the Orion Nebula and Bouy et al. (2014), using the DECam wild-field camera centered on NGC 1980, confirmed the existence of foreground PMS stars clustered around NGC 1980. They concluded that NGC 1980 and NGC 1981 must have similar distances and ages. This scenario of star formation in the Orion Nebula is incompatible with the age determined by Kharchenko et al. (2005) for NGC 1981 of 32 Myrs. It is not expected, at first, that NGC 1981 is much older than the others surrounding clusters, if they present a common origin.

Despite the efforts to better understand the astrophysical processes occurring in the Orion Nebula and its surroundings, the metallicity and chemical abundances of NGC 1981 have not been given particular attention, since most studies are interested in a general analysis of the Orion formation complex.

In this sense, from NGC 1981's spectroscopy, we aim to derive, for the first time, the stellar parameters and abundances of the cluster members to determine the metallicity and constrain the isochrone fitting. Astrometric and photometric data from the GAIA mission together with our improved decontamination method (Angelo et al. 2019; Ferreira et al. 2021) allow us to determine the astrophysical parameters of the cluster. An isochrone fittig, combined with the parameters that will be determined from the spectroscopy, will help to solve the NGC 1981's age discrepancy. In Sect. 2 we present the observational data and the spectroscopic data reduction procedure. In Sect. 3 we present the methodology to determine the astrophysical parameters. In Sect. 4 we discuss the results from our decontamination method and in Sect. 5 the [M/H] and V_{rad} analysis. The conclusions are presented in Sect. 6.

2. Observational Data

The detailed study of the Orion Nebula surrounding clusters, still immersed in their progenitor clouds, is helpfull to better understand the star formation. In these ambients, the stellar feedback and winds, mainly from the massive stars, and the complex interplay between star formation and stellar dynamics require a joint investigation which ideally combines photometric, astrometric and spectroscopic information. This strategy is essential to access the pecularities of young clusters, as is the case of NGC 1981.

In order to determine the astrophysical parameters and to generate a membership list for NGC 1981 we have used the astrometric and photometric data from GAIA data release 2 (DR2) and the early data release (EDR3) (Gaia Collaboration et al. 2018, 2021) that were available at the time. The quality filters from Arenou et al. (2018) were applied on the DR2 data, while the quality filters from Lindegren et al. (2021) and Riello et al. (2021) were used on the EDR3 to remove poor quality data.

To complement this data with radial velocities, metallicities and chemical abundances from the cluster's members, we have collected with the 2.15-m Jorge Sahade telescope from CASLEO (Argentina), in 2015, medium resolution spectrocopic data (R ~ 12 000) of the stars identified as members by MAIA10. The telescope was coupled with the Échelle spectrograph centred at 4500 Å, covering the optical and the near ultraviolet (UV). We have also observed spectroscopic data with 1.6-m telescope Perkin-Elmer from OPD (Brazil) in 2021 and 2022. It was coupled with the medium resolution spectrograph Coudé (R ~ 16 000) centred in the Hα line, with 50 Å of wavelength range.

The data obtained with the both spectrographs were reduced using standard IRAF routines, like flat-field corrections, wavelength calibration with ThAr lamp, CCD bias correction and cosmic ray extraction. Since the spectra were not flux calibrated, it was needed to use IRAF routines to do also the continuum normalization.

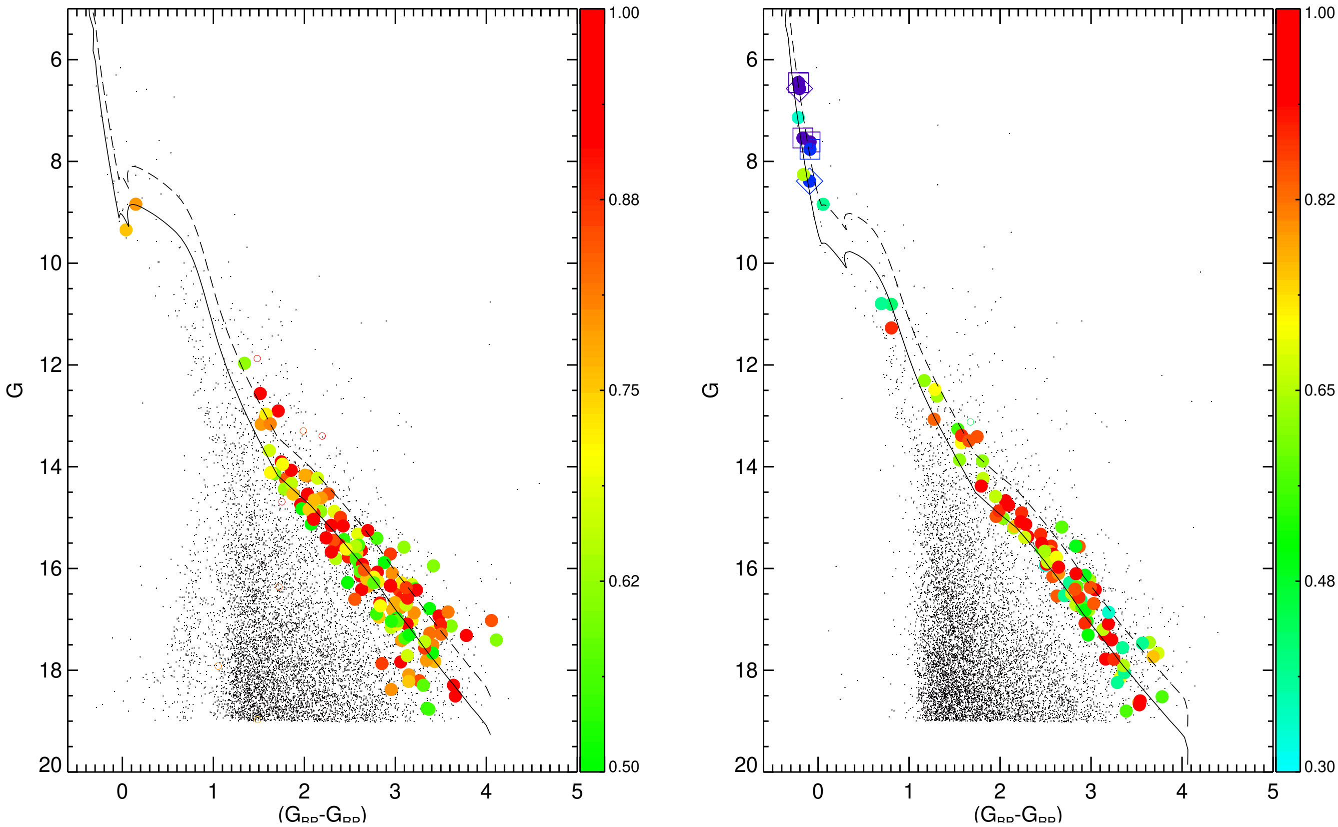

Figure 1. Decontaminated colour-magnitude diagram for NGC 1977 (left panel) and NGC 1981 (right panel). The larger filled symbols identify clusters members from our membership list. The small purple and black dots represent field stars. Stars marked with diamonds are cluster members according to our preliminary analysis based on radial velocity dispersion. The squares identify the brightest member stars according to MAIA10. The symbol colours follow the membership probability scale according to the bar on the right side of the figure.

Table 1. Astrophysical parameters of NGC 1981 and NGC 1977 derived following the methodology of Ferreira et al. (2021) and Angelo et al. (2019).

	NGC 1977	NGC 1981
RA (°)	83.85	83.83
DEC (°)	-4.81	-4.35
μ_α (mas/yr)	1.40	1.2
μ_δ (mas/yr)	-0.75	0.6
ϖ (mas)	2.56	2.53
$R_{\rm lim}$ (”)	1000 ± 57	1062 ± 57
E(B-V) (mag)	0.07 ± 0.04	0.03 ± 0.04
$(M\text{-}m)_o$ (pc)	417 ± 54	381 ± 50
Idade (Myrs)	4 ± 1	8 ± 1
[M/H] (dex)	0.0152 ± 0.02	0.0152 ± 0.01
$V_{\rm rad}$ (km s^{-1})	-	41.6 ± 8.3

3. Methodology

Before applying the decontamination method to generate a membership list it is needed to know the atrophysical parameters of the cluster, i.e. its centre position (RA, DEC), proper motion (μ_α & μ_δ) and parallax (ϖ). To determine these parameters we have used the methodology of Ferreira et al. (2021), that consist in determine the most recurrent value from the distribution.

The main assumption of this method is that stars from a cluster born from the same parental cloud, have similar kinematics components, distances and are spatially nearby to each other. As the EDR3 was in its early data acess, we had decided to use the data release that was exhaustively tested, the DR2, to assure that we were using the most reliable data. However, the EDR3 precision is better than the DR2 Gaia Collaboration et al. (2021), so we have made the same procedure to both data releases and, almost, no differences has been noticed.

We have chosen a region of 45 arcmin centred at the centre determined by MAIA10. This region was chosen to remove the contamination from M42, which is far below the declination of NGC 1981, but still contaminates the data because both clusters have similar parameters. In this region, to make it easier to identify NGC 1981 we have applied three filters: (i) limit the magnitude in the G band at most 19 mag, to remove the faintest stars with low quality data; (ii) limit the color $G_{\rm BP} - G_{\rm RP} \leq 2.5$, to remove the reddest stars; and (iii) restrict the parallax to $\varpi \geq 1.0$, to remove sources distant by more than 1 kpc. After these filters had been applied, a gaussian fit has been made in the astrometric data to determine the peak of the distribution in RA, DEC, μ_α, μ_δ and ϖ.

With these parameters a RDP has been made, by generating concentric circular rings centred at the new center derived in the previous step, so that limiting radius of the cluster could be determined. After these parameters have been determined, we applied the decontamination method of Angelo et al. (2019), which uses the 3D astrometric space (μ_α, μ_δ and ϖ) to atribute the membership probability for each star. The method compares the cluster region defined by its centre and its limiting radius to an annular control field. As stars from a cluster have similar kinematics, it is expected that the group of stars in the cluster region will appear much more tightly distributed than the field stars on the astro-

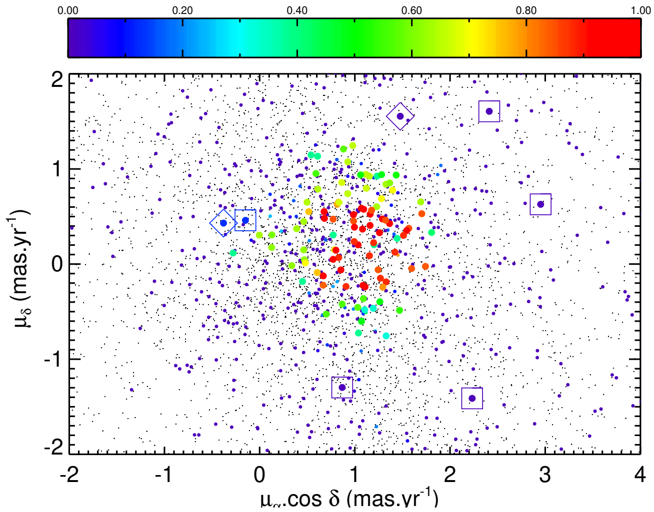

FIGURE 2. Vector point diagram of NGC 1981. Colour and symbols are the same of Fig. 1.

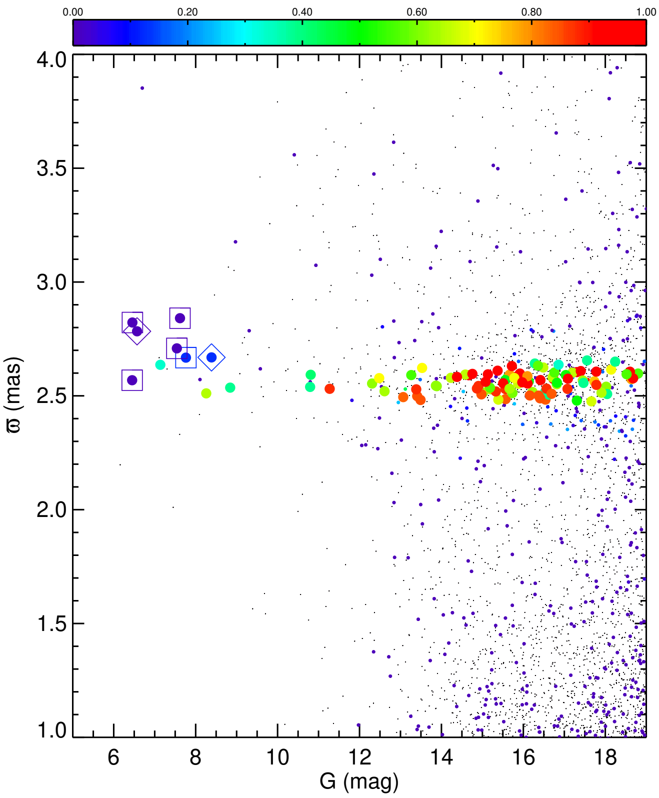

FIGURE 3. G magnitude x parallax (ϖ) plot for stars in the direction of NGC 1981. Colour and symbols are the same of Fig. 1.

metric 3D space. A membership is assigned to the stars present in the cluster region by a gaussian ditribution probability and an entropic-like function (for more details see Angelo et al. (2019)).

With the star members determined by the decontamination method an isochrone fitting has been made to derive the distance modulus, the age, the reddening and the metallicity through the photometric data obtained from GAIA.

4. Astrometric and Photometric Analysis

At first, we have tried to determine the stellar parameters of NGC 1981, however we noticed that NGC 1981 is contaminated spatially and also in the astrometric 3D space by its neighbour NGC 1977, which make harder to determinate the astrophyscal parameters of NGC 1981 precisely. Since they are clusters formed in the same environment, it is not a surprise that they have some similarities in their astrophysical parameters.

So we have decided to remove NGC 1977 data from the sample before analyzing and determining the parameters of NGC 1981. Since NGC 1977 is more detached in the astrometric 3D space and has more stellar content than NGC 1981, it is easier to separete it from the field stars and others nearby clusters. So we have applied a procedure described in Sect. 3 to identify and characterize NGC 1977 and their members.

With the isochrone fitting, which is shown in Fig. 1 on the left panel, we have determined the distance modulus, the metallicity, the reddening and, in special, its age as being 4 ± 2 Myrs. Then we have removed the stars with membership probability until 50 percent from NGC 1981 sample.

Now, with the stars from NGC 1977 removed, it was easier do determine the astrophysical parameters, generate a membership list and to perform an isochrone fitting to characterize NGC 1981 (Fig. 1 right panel). The parameters derived for NGC 1977 and NGC 1981 are shown in the Tab. 1. Almost every parameters have the same values, expect for the more negative declination and μ_δ and the higher reddening for NGC 1977 (also expected from the dust distribution towards this cluster). The age determination of NGC 1981 resulted in 8 ± 1 Myrs, which is consistent with the age determination done by MAIA10, but widely different from the results of Kharchenko et al. (2005). Such results reinforce the sequential star formation scenario proposed by MAIA10 and Bouy et al. (2014).

It can be noticed in Fig. 1 on the right panel, that the brightest stars from the membership list of MAIA10, which are marked in squares, are receiving low membership probability in our analysis of the 3D astrometric space. This can be explained by the great dispersion that these stars have, as can promptly be seen in Figs. 2 and 3, where the stars marked with a square are the same stars from Fig. 1. As the method uses the astrometric 3D space and the stars do not have similar properties, like parallax and proper motion, they are receiving low membership probability.

5. Spectroscopy of NGC 1981

As discussed in Sect. 4 only the astrometric and photometric data are not enough to properly assign the membership probability for the case of NGC 1981. Therefore, to complement these data we have used the spectroscopic data from the members of NGC 1981, to impose a bound between the isochrone fitting, the astrometric analysis and the parameters that can be derived from spectroscopic data, like metallicity and V_{rad}.

However, due to the bad weather conditions faced during the observations, only the brightest stars from the membership list of MAIA10 were spectroscopically observed and we could not achieve the desired S/N to make a chemical abundance analysis with these observations. We have only been able to calculate the V_{rad} from the Hydrogen lines present in the spectra and to make an average of the values. The analysis resulted in a radial velocity $V_{rad} = 41.6 \pm 8.3\,\mathrm{km\,s^{-1}}$, also reported in Tab. 1.

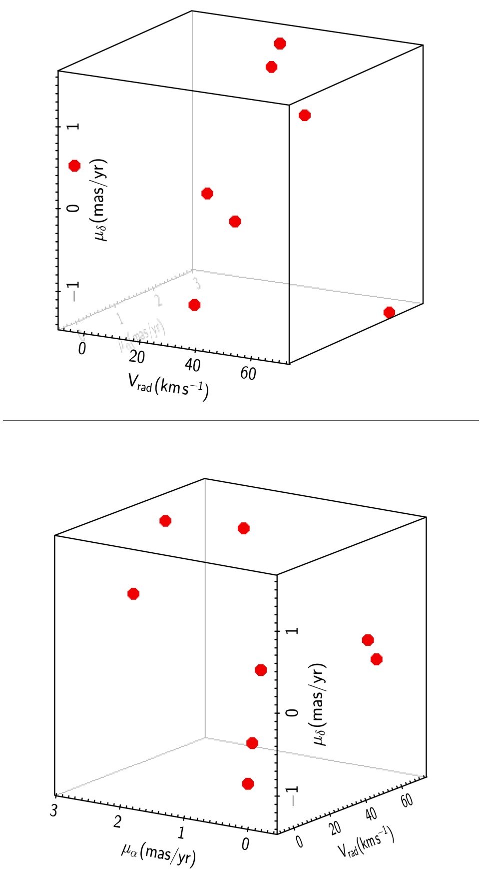

Figure 4. 3D velocity map (μ_α, μ_δ and V_{rad}) of the stars of NGC 1981 observed spectroscopically.

If we assume that the members are only the stars with $V_{\rm rad}$ within the uncertainties, two stars will be included. These stars are marked with a diamond in Figs. 1, 2 and 3. With another isochrone fitting, now considering that these two stars are members of NGC 1981, the only parameter that changes is the reddening, that goes from $E(B-V) = 0.05$ to $E(B-V) = 0.03$.

The same dispersion that can be noticed in the proper motion space (Fig. 2), can also be seen in the radial velocities $V_{\rm rad}$. In Fig. 4 the 3D velocity map (μ_α, μ_δ and $V_{\rm rad}$) is shown. If the main features of a cluster, that is, a similar kinematics of its members, is taken into account, then one might expect that these stars should be near each other in the 3D velocity map.

NGC 1981 is in the gas-free phase, so the first generation of stars had enough time to evolve and release energy in the ISM in the form of supernovae and winds, that could lead to the actual sparse structure. This great dispersion in the astrometric data of the brigthest stars of the cluster suggests that NGC 1981 is undergoing some disruptive processes that make it survive only for a few million years.

6. Conclusion

Through the high precision astrometric and photometric data from GAIA DR2 and EDR3 we have applied our astrometric decontamination method to characterize the clusters surrouding the Orion Nebula, NGC 1977 and NGC 1981. In order to study the peculiarities of the young cluster NGC 1981 we have collected spectroscopic data aiming to impose bounds in the isochrone fitting, looking for a better determination of its astrophysical parameters.

We have determined the centre position, proper motion and parallax for both clusters. With these parameters RDPs have been built to determine the cluster limiting radius. We have also made an isochrone fitting to derive the reddening, distance modulus, age and metallicity. NGC 1977 and NGC 1981 have similar characteristics, being the main difference in the reddening, position and proper motion in DEC and in the age.

The ages of NGC 1981 and NGC 1977 of 8 Myrs and 4 Myrs, respectively, reinforce the sequential star formation scenario in Orion Nebula as has been suggested by MAIA10 and Bouy et al. (2014).

The great dispersion in the astrometic data of NGC 1981 (μ_α, μ_δ, ϖ and $V_{\rm rad}$) suggests that the cluster may be undergoing some disruptive processes that will lead its stellar content to be dissipated in the Galactic field.

Besides the $V_{\rm rad}$ analysis have helped to understand the peculiarities of NGC 1981, it is still necessary to perform a detailed study of the metallicity and chemical abundances to impose bounds in the astrophysical parameters determination. Bottom line, to study the surrounding clusters of the Orion Nebula may help us to understand the star formation in the region and also to provide constraints to the star cluster formation process as well as their dynamical properties.

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