

Unveiling the star formation history of the Orion Nebula region

P. H. F. B. Braz¹, W. J. B. Corradi^{2,1}, A. Roman-Lopes³, O. J. Katime-Santrich⁴, M. S. Angelo⁵, F. S. S. Maia⁶, E. B. Amôres⁷, F. A. Ferreira¹, J. F. C. Santos Jr.¹, & A. E. Piatti^{8,9}

¹ Departamento de Física, ICEx, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte, MG, Brazil e-mail: pedrobraz@ufmg.br e-mail: filipeandradeferreira@hotmail.com e-mail: jsantos@fisica.ufmg.br

² Laboratório Nacional de Astrofísica, R. Estados Unidos, 154, 37504-364, Itajubá, MG, Brazil e-mail: wbcorradi@lna.br

³ Department of Astronomy, Universidad de La Serena, Av. Raul Bitran #1302, La Serena, Chile e-mail: aroman@userena.cl

⁴ Departamento de Ciências Exatas DECEX, Universidade Estadual de Santa Cruz, Rodovia Jorge Amado km 16, 45662-900 Ilhéus, Brazil e-mail: ojksantrich@uesc.br

⁵ Centro Federal de Educação Tecnológica de Minas Gerais, Av. Amazonas, 7675, 30510-000 Belo Horizonte, MG, Brazil e-mail: mateusangelo@cefetmg.br

⁶ Instituto de Física, Universidade Federal do Rio de Janeiro, 21941-972 Rio de Janeiro, Brazil e-mail: ffsmaia@if.ufrj.br

⁷ Departamento de Física, Universidade Estadual de Feira de Santana (UEFS), Av. Transnordestina, S/N, CEP 44036-900 Feira de Santana, BA, Brazil e-mail: ebamores@uefs.br

⁸ Instituto Interdisciplinario de Ciencias Básicas (ICB), CONICET-UNCuyo, Padre J. Contreras 1300, M5502JMA, Mendoza, Argentina e-mail: andres.piatti@fcen.uncu.edu.ar

⁹ Consejo Nacional de Investigaciones Científicas y Técnicas, Godoy Cruz 2290, C1425FQB, Buenos Aires, Argentina e-mail: andres.piatti@fcen.uncu.edu.ar

Abstract. Open clusters (OCs) belonging to star-forming complexes are remnants from the initial stellar generations. Recently, it has been suggested a sequential star formation scenario for the Orion Nebula (ON) region, where the older OCs, such as NGC 1981 and NGC 1980, together with the feedback from the massive stars of the region, triggered the star formation events in the younger stellar populations, such as in NGC 1977, OMC-2 and 3 and M42. NGC 1981 is currently located in a relatively dust-free field, while NGC 1977, located approximately 20' south of NGC 1981, remains embedded within its progenitor cloud. The different evolutionary states, together with the proposed sequential star formation scenario, make these clusters interesting science cases to investigate star and cluster formation and evolution. To unveil the star formation history of the ON region, we used astrometric, photometric data from Gaia DR3 to decontaminate and determine the fundamental, astrophysical, and structural parameters of the OCs and to generate a membership list. Through optical and infrared spectroscopy collected at SOAR, OPD and from APOGEE survey, we were able to make a joint analysis, improving the membership probability and constrain the isochrone fitting. To complement this study, we have collected polarimetric (OPD) and high-resolution spectroscopic (GHOST/GEMINI) data, which will be used to perform a detailed chemical abundances and interstellar medium analysis.

Resumo. Aglomerados abertos (AAs) pertencentes a complexos de formação estelares são remanentes das primeiras gerações estelares. Recentemente, foi sugerido um cenário de formação estelar sequencial para a Nebulosa de Órion (NO), onde os aglomerados mais antigos, tais quais NGC 1980 e NGC 1981, juntamente com o feedback das estrelas massivas da região, acionaram os eventos de formação estelar nas populações mais jovens, como em NGC 1977, OMC-2 e 3 e M42. NGC 1981 habita em uma região relativamente livre de gás, enquanto NGC 1977, que está localizado a 20' ao sul de NGC 1981, continua embebido em sua nuvem progenitora. Os diferentes estágios evolutivos, junto com o cenário de formação estelar sequencial, fazem desses aglomerados um interessante caso científico para estudar a formação e evolução de AAs. Para desvendar a história de formação estelar da região da NO, nos usamos os dados astrométricos e fotométricos do Gaia DR3 para descontaminar e determinar os parâmetros fundamentais, astrofísicos e estruturais dos aglomerados e para gerar uma lista de membros. Dados espectroscópicos no óptico e infravermelho coletados no SOAR, OPD e do catálogo do APOGEE foram utilizados para fazer uma análise conjunta, melhorando a probabilidade de pertencimento e para restringir os parâmetros no ajuste de isócronas. Para complementar esse estudo, nos estamos coletando dados polarimétricos (OPD) e espectroscopia de alta resolução (GHOST/Gemini), que permitirá uma análise detalhada da abundância química e do meio interestelar.

Keywords. Stars: formation – open clusters and associations: individual: NGC 1977 – open clusters and associations: individual: NGC 1981

1. Introduction

Open clusters (OCs) belonging to star-forming complexes are the leftovers from 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 (Cantat-Gaudin et al. 2018; Ferreira et al. 2020; Angelo et al. 2023). Young OCs can be found in distinct evolutionary phases, such as 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. Among the various star-forming regions, the Orion complex stands out

as an excellent laboratory for studying the star formation process due its proximity and richness in ongoing star formation.

Blaauw (1964) first proposed that the Orion OB1 association was formed by a sequential star formation process that propagated from OB1a to OB1d. More recent studies reinforced this scenario by characterizing their distances, positions, and ages (e.g. Bally 2008; Elias, et al. 2009; Bouy, & Alves 2015). In another perspective, Großschedl et al. (2021) traced back the positions of the Orion complex groups by analysing their kinematics and suggested that a sequence of supernova explosions originating from the Orion X (Bouy, & Alves 2015) region would have helped to shape the spatial and kinematic distribution of the Orion complex.

Besides these star formation scenarios being quite different, they are not mutually exclusive, and it is feasible that both processes occurred together.

In past years, trying to prove the youth of the OC NGC 1981, Maia et al. (2010) suggested a sequential star formation scenario for the clusters around the Orion Nebula (ON) region. Later, Bouy et al. (2014) hypothesized that the earlier clusters that were formed around the ON, such as NGC 1980 and NGC 1981, together with the feedback of the massive stellar content, played a crucial role in triggering the subsequent star formation events in the ON and its surrounding younger populations, like NGC 1977, OMC-2 and 3 and M42.

NGC 1981 is a young, sparse cluster located 1° north from the ON. 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 through supernovae and/or stellar winds. NGC 1981 was determined with an age of 32 Myrs (Kharchenko, et al. 2005), which is much older than the other nearby clusters, as NGC 1977, located about $20'$ southward of NGC 1981, with an age of 2 Myrs (Dias, et al. 2021) and, further below, M42 with less than 1 Myr (Pabst, et al. 2020).

As most studies are interested in general analysis of the Orion complex (large scales), the clusters of this region (small scales) have not received particular attention. The possible interacting case of NGC 1977 and NGC 1981 that surround the ON could provide enough information to deepen the understanding of the astrophysical processes of cluster formation and evolution. Furthermore, this can provide enough insights to help us to understand the star formation history of the ON region.

In this sense, we aim to characterize the ON surrounding OCs NGC 1977 and NGC 1981. We will perform a decontamination method using the precise astrometric and photometric information from *Gaia* DR3 (Gaia Collaboration et al. 2021). To complement these data, we will use spectroscopic data from the APOGEE-2 survey (Abdurro'uf, et al. 2022) and from spectra collected at Observatório Pico dos Dias (OPD), Complejo Astronomico el Leoncito (CASLEO) to derive the metallicity and radial velocity (V_{rad}) of the cluster members to constrain the isochrone fitting, performing a joint analysis combining astrometric, photometric and spectroscopic data.

This manuscript is organized as in following. In Sect. 2 we present the observational data and the spectroscopic data reduction procedure. In Sect. 3 we present the methodology to determine the fundamental, astrophysical and structural parameters. In Sect. 4 we discuss the results from the joint analysis. The conclusions are presented in Sect. 5.

2. Observational Data

The detailed study of the ON surrounding clusters, still immersed in their progenitor clouds, is helpful 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 peculiarities of young clusters, as is the case of NGC 1977 and NGC 1981.

In order to determine the astrophysical parameters and to generate a membership list for NGC 1977 and NGC 1981 we have used the astrometric and photometric data from *Gaia* DR3 (Gaia Collaboration et al. 2021). The quality filters from Lindegren

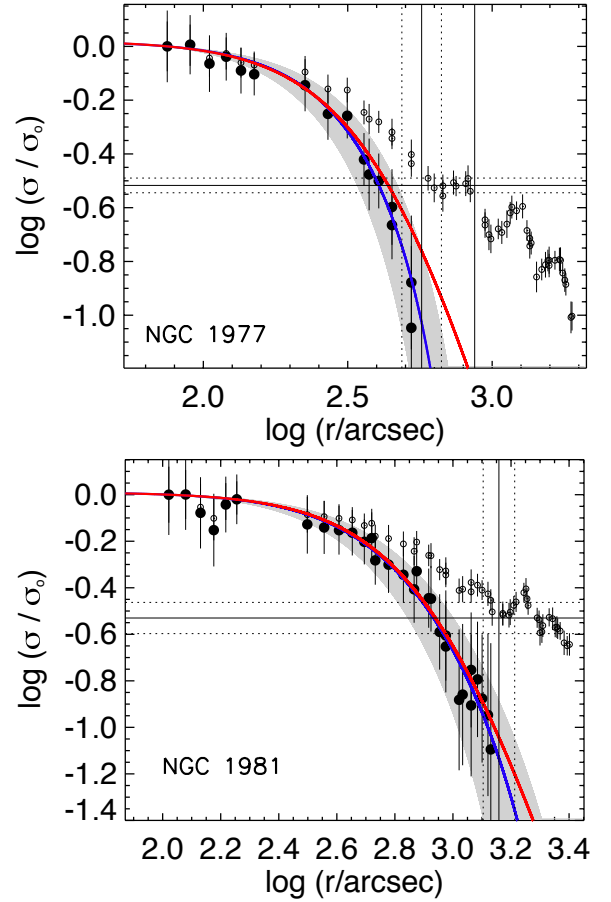


FIGURE 1. Filled circles represent the background-subtracted and normalized profiles, to which we fitted King (blue line) and Plummer profiles (red lines). The profiles are normalized to unity at the innermost bin. Open circles represent non-subtracted RDPs, and the mean background density (σ_{bg}) is indicated by the continuous horizontal line. The continuous and dashed vertical lines show, respectively, the cluster limiting radius (R_{lim}) and its uncertainties.

et al. (2021) and Riello et al. (2021) were used on the DR3 to remove poor quality data.

To complement this data with radial velocities and metallicities from the cluster's members, we have collected with the 2.15-m Jorge Sahade telescope from CASLEO (Argentina), in 2015, medium resolution spectroscopic data ($R \sim 12\,000$) of the stars identified as members by Maia et al. (2010). The telescope was coupled with the Échelle spectrograph centred at 4500 \AA , 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 ($R \sim 16\,000$) centred in the $H\alpha$ line, with 50 \AA 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.

TABLE 1. Astrophysical and structural parameters of NGC 1977 and NGC 1981 derived following the methodology of Angelo, et al. (2019) and Ferreira et al. (2020).

	NGC 1977	NGC 1981
RA (°)	83.87	83.81
DEC (°)	-4.79	-4.35
μ_α (mas/yr)	1.40 ± 0.39	1.2 ± 0.39
μ_δ (mas/yr)	-0.75 ± 0.70	0.6 ± 0.47
ϖ (mas)	2.56 ± 0.04	2.53 ± 0.04
σ_0 (stars arcmin ⁻²)	0.40 ± 0.06	0.22 ± 0.01
r_c (′)	8.20 ± 1.54	12.60 ± 1.50
r_t (′)	14.00 ± 2.06	45.1 ± 13.6
r_{hm} (′)	10.21	22.88
c	0.23	0.55

3. Fundamental and Structural Parameters

To determine the cluster parameters, i.e. its centre position (RA, DEC), μ_α , μ_δ and ϖ , we have used the methodology of Ferreira et al. (2020), which consists of a Gaussian fit to determine the peak of the distribution. To find the most recurrent value from the distribution, an initial guess is used for better convergence of the fit, thus we selected stars within 10′ from the literature centres of the clusters (Maia et al. 2010; Cantat-Gaudin et al. 2018).

Once the centres have been determined, we fit the King’s (King 1962) profile, to determine the core (r_c) and tidal (r_t) radius, and the Plummer’s profile (Plummer 1911), to determine the half-mass radius (r_{hm}). While the King profile provides a better fit in the external regions, the Plummer profile better constrain the inner regions (e.g. Angelo et al. 2023).

The King (red) and Plummer (blue) profile are shown for NGC 1977 (left panel) and NGC 1981 (right panel) in Fig. 1. By performing the King profile, it is possible to evaluate the concentration of the clusters through the relation $c = \log(r_t/r_c)$. Both clusters have a very low concentration parameter due to their sparse structure and very low stellar content. Furthermore, since these are very young clusters, they may be in an unstable dynamic stage, which may change with the cluster evolution. The fundamental and structural parameters are shown in Table 1. The similarity between their fundamental parameters may also be indicative of a binarity system.

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 assign the membership probability for each star. The method compares the cluster region defined by a circular area at its centre, limited by its r_t , to an annular control field. As stars from a cluster have similar kinematics, it is expected that the members of the cluster will appear much more tightly distributed than the field stars in the astrometric 3D space. Membership is assigned to the stars present in the cluster region by a Gaussian distribution probability and an entropic-like function.

4. Joint Analysis

With the cluster members, it is possible to perform a joint analysis with the spectroscopic data to constrain the isochrone fitting. To perform this joint analysis, we crossmatch the members determined by the above-mentioned method to the APOGEE data to derive the metallicity and V_{rad} , which we have used to expand our membership probability space. The membership probability from the metallicity and V_{rad} were calculated by using a normal probability density function. Then, we perform a productory of all these probability and remove stars with a joint membership

TABLE 2. Metallicity and V_{rad} determined through spectroscopic data from the members of the joint analysis.

	NGC 1977	NGC 1981
[M/H] (dex)	-0.26 ± 0.11	-0.24 ± 0.20
V_{rad} (km s ⁻¹)	30.00 ± 2.45	30.23 ± 1.68

probability of less than 60 per cent. With this new membership list, we determined the mean metallicity and V_{rad} and the respective standard deviation for both clusters, which is presented in Table 2. There is almost no difference between the clusters in these parameters, which reinforces the probable binary system scenario between them.

When the probability space, which is shown in Fig. 2 for NGC 1977 (top panels) and NGC 1981 (bottom panels), is taken into account, we can remove stars that appear to be part of the cluster in the photometric and projected astrometric data from *Gaia*, but they exhibit different features in the spectroscopy. In the case of NGC 1977, it can be seen that some stars classified as members in the astrometric space do not have coherence in the metallicity and in the V_{rad} , presenting differences up to 0.7 dex and 20 km s⁻¹, respectively. This result clarifies the importance of the joint analysis, since with this method, we can deeply investigate the characteristics of the clusters, leading to more precise information.

For the case of NGC 1981, a similar scenario can be seen. However, all the stars that were removed in this joint analysis are B stars, which are commonly binaries and have poor metallicity determination. Furthermore, as NGC 1981 is a cluster that may be undergoing a disruptive process (Maia et al. 2010), these stars may have been ejected during its formation, and they may be potential runaway stars. Therefore, we cannot rule them out as probable members, since they can have different kinematics when compared with low-mass stars.

Using the metallicity determined through spectroscopy as a prior, we have used the SIESTA code (Ferreira, et al. 2024) to fit the isochrones shown in Fig. 3. The isochrone fitting of NGC 1981 presents a double solution, one solution is closer, younger and less reddening, while the second one is farther, older and more reddening. This is because NGC 1981 Northern hemisphere is in a region relatively free of gas, while its Southern hemisphere is contaminated by the progenitor cloud of NGC 1977. To further resolve this issue, we will have to account for differential reddening.

5. Conclusions

With our decontamination method and performing a study with *Gaia* DR3 and spectroscopic data, we found that NGC 1977 and NGC 1981 present great similarity in their parameters, being a probable binary system. Both clusters present large r_c , suggesting that they have a more sparse distribution of their stellar content. Besides that, no clear difference can be seen in the V_{rad} , but NGC 1977 is slightly more metallic than NGC 1981.

The joint analysis allowed us to better assign membership to the stars, expanding our probability space. We could remove stars that appear to have a distinct formation, not being part of NGC 1977. The case of NGC 1981 should be treated carefully, because its B stars were assigned with low membership probability due to their distinct parameters. However, those stars may have been ejected from the clusters.

Moreover, with the spectroscopic data, we could constrain the isochrone fitting, improving the parameter determination. NGC 1981 exhibits a dual solution in this procedure, probably

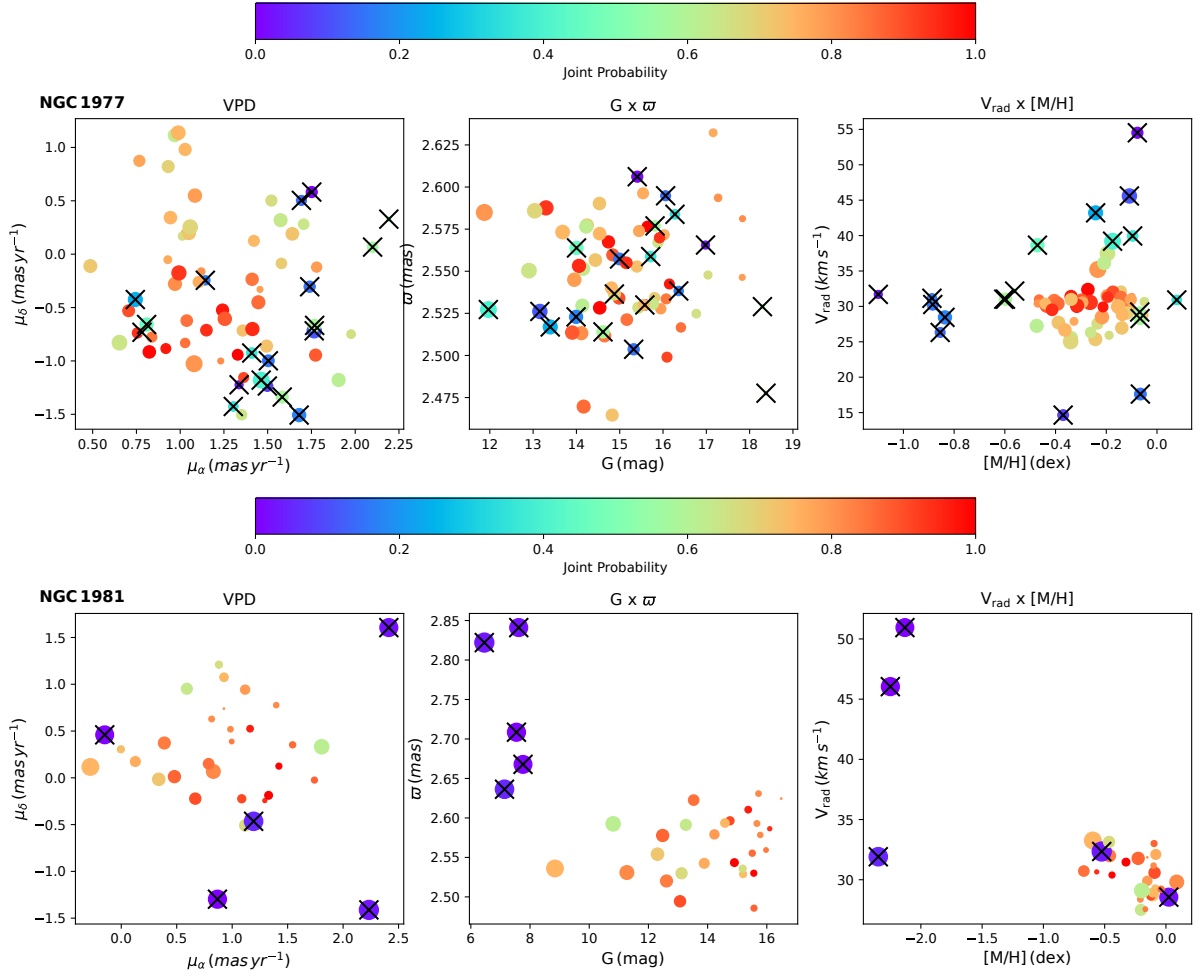


FIGURE 2. Joint probability space for the cluster members. The panels show the VPD, ϖ versus G mag and the V_{rad} versus metallicity. The size of the circles is proportional to the G magnitude and the colors represent the joint membership probability following the colour bar at the top of the figure. Stars marked with a “X” are those with membership probability less than 60 per cent.

caused by the nebula contamination in its southern hemisphere. We aim to apply a differential reddening to solve this issue in the future.

Acknowledgements. The authors acknowledge the Brazilian Agencies FAPEMIG, CAPES, CNPq, and PRPq/UFGM/FUNDEP for the financial support. W.J.B. Corradi acknowledged the support from Laboratório Nacional de Astrofísica LNA/MCTI and the support from CNPq - BRICS 440142/2022-9, FAPEMIG APQ 02493-22 and FNDCT/FINEP/REF 0180/22.

References

Abdurro’uf, Accetta, K., Aerts, C., et al. 2022, *The Astrophysical Journal Supplement Series*, 259, 35.
 Angelo, M. S., Santos, J. F. C., Corradi, W. J. B., et al. 2019, *Astronomy and Astrophysics*, 624, A8.
 Angelo, M. S., Santos, J. F. C., Maia, F. F. S., et al. 2023, *MNRAS*, 522, 1, 956.
 Bally, J. 2008, *Handbook of Star Forming Regions*, Volume I, 4, 459
 Blaauw, A. 1964, *Annual Review of Astronomy and Astrophysics*, 2, 213.
 Bouy, H., Alves, J., Bertin, E., et al. 2014, *A&A*, 564, A29.
 Bouy, H., & Alves, J. 2015, *Astronomy and Astrophysics*, 584, A26.
 Cantat-Gaudin, T., Jordi, C., Vallenari, A., et al. 2018, *A&A*, 618, A93.
 Dias, W. S., Monteiro, H., Moitinho, A., et al. 2021, *Monthly Notices of the Royal Astronomical Society*, 504, 356.
 Elias, F., Alfaro, E. J., & Cabrera-Caño, J. 2009, *Monthly Notices of the Royal Astronomical Society*, 397, 2.
 Ferreira, F. A., Corradi, W. J. B., Maia, F. F. S., et al. 2020, *MNRAS*, 496, 2, 2021.
 Ferreira, B. P. L., Santos, J. F. C., Dias, B., et al. 2024, *Monthly Notices of the Royal Astronomical Society*, 533, 4210.

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, *A&A*, 649, A1.
 Großschedl, J. E., Alves, J., Meingast, S., et al. 2021, *A&A*, 645, A137.
 Kharchenko, N. V., Piskunov, A. E., Röser, S., et al. 2005, *Astronomy and Astrophysics*, 438, 1163.
 King, I. 1962, *The Astronomical Journal*, 67, 471.
 Lindegren, L., Klioner, S. A., Hernández, J., et al. 2021, *A&A*, 649, A2.
 Maia, F. F. S., Corradi, W. J. B., & Santos, J. F. C. 2010, *MNRAS*, 407, 3, 1875.
 Pabst, C. H. M., Goicoechea, J. R., Teyssier, D., et al. 2020, *Astronomy and Astrophysics*, 639, A2.
 Plummer, H. C. 1911, *Monthly Notices of the Royal Astronomical Society*, 71, 460.
 Riello, M., De Angeli, F., Evans, D. W., et al. 2021, *A&A*, 649, A3.

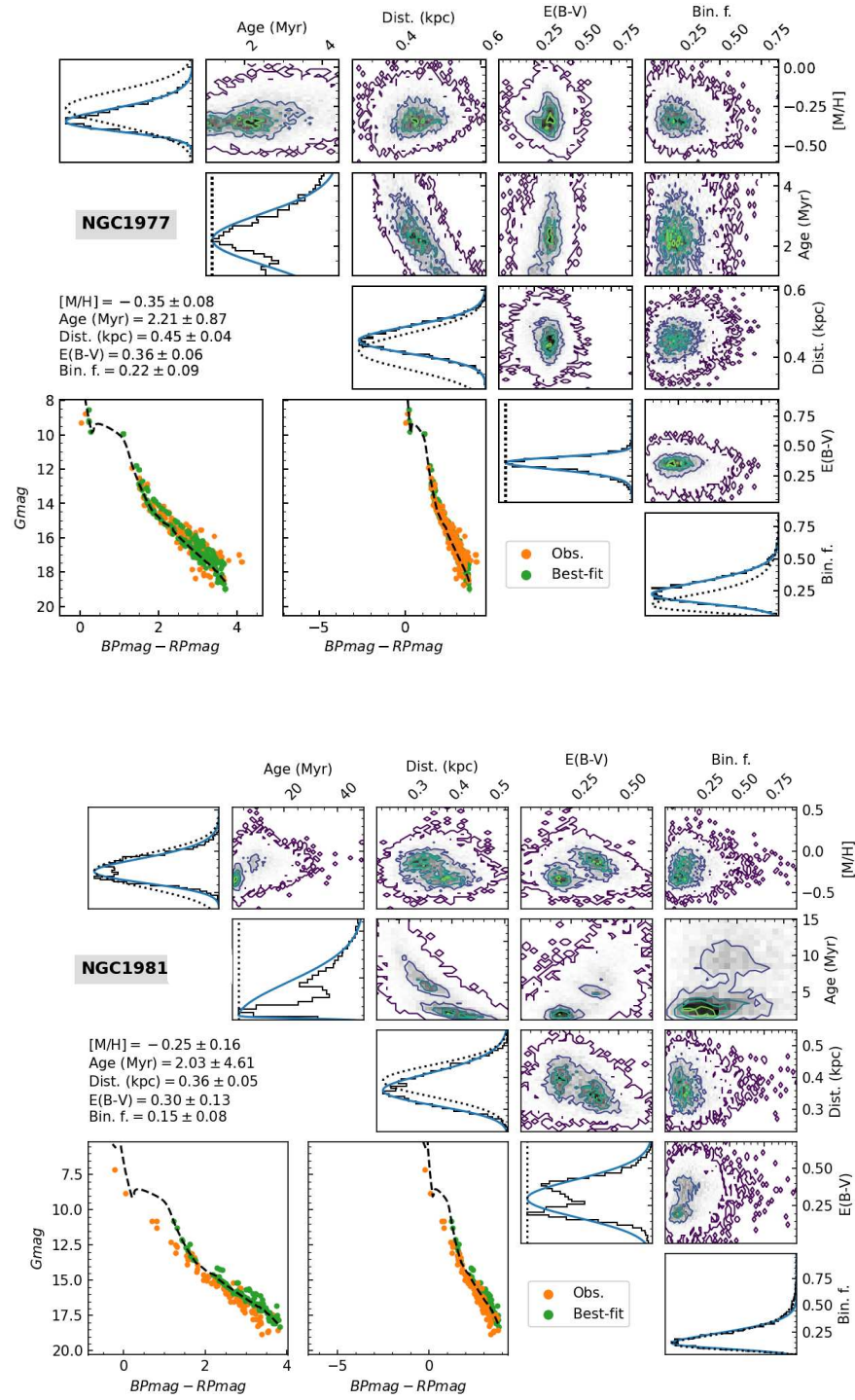


FIGURE 3. Isochrone fitting from SIESTA code (Ferreira, et al. 2024). On the top panel is shown the corner plot for NGC 1977 and on the bottom panel for NGC 1981.