Bayesian analysis of five open clusters in the Milky Way

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Resumen / Presentamos resultados derivados de la aplicación de nuestro conjunto de códigos numéricos *Automated Stellar Cluster Analysis* sobre cinco cúmulos abiertos mayormente ignorados, ubicados en el tercer cuadrante de la Vía Láctea. Nuestra fotometría UBV Johnson-Kron-Cousin fue combinada con datos de la segunda publicación de datos de la misión Gaia. Obtenemos probabilidades de membresía y finalmente se utiliza un algoritmo Bayesiano de tipo *Markov chain Monte Carlo* para derivar los parámetros fundamentales de los cúmulos.

Abstract / We present results derived from the application of our suite of numerical codes *Automated Stellar Cluster Analysis* on five mostly overlooked open clusters, located in the third quadrant of the Milky Way. Our UBV Johnson-Kron-Cousin photometry was combined with data from the second data release of the Gaia survey. Membership probabilities are obtained and finally a Bayesian Markov chain Monte Carlo algorithm is used to derive the fundamental parameters of the clusters.

Keywords / methods: statistical — galaxies: star clusters: general — open clusters and associations: general — techniques: photometric — parallaxes — proper motions

1. Introduction

The five clusters analyzed in this article are: Ruprecht 41, Ruprecht 42, Ruprecht 44, Ruprecht 152, and Haffner 14 (RUP41, RUP42, RUP44, RUP152, HAF14). These are all mostly overlooked open clusters located in the third quadrant of the Milky Way. We cross-matched our UBV Johnson-Kron-Cousin photometry, obtained using the 1.0 m Swope telescope* at Las Campanas, Chile, with publicly available data from the second data release of the Gaia survey (DR2). This allows us to add the G magnitude along with parallax and proper motions data, to our full set of observed stars.

Our suite of numerical codes *Automated Stellar Cluster Analysis* (ASteCA) (Perren et al., 2015) is a powerful tool especially developed to perform an automatic analysis of observational cluster data (structural, photometric, and if available, parallax and proper motions). A comprehensive study of stellar coordinates allows the code to determine center and cluster radius values. Following this, membership probabilities are assigned to all stars within the defined cluster regions through a Bayesian decontamination algorithm. This method combines photometric data with parallax and proper motions to better estimate the per-star probability of being a cluster member. Finally, a Bayesian Markov chain Monte Carlo (MCMC) parallel algorithm is applied to derive the fundamental parameters: metallicities, ages, extinctions, distances, and masses.

*`https://obs.carnegiescience.edu/swope`

2. Analysis

The analyzed frames for two of the five clusters (RUP44 and HAF14) are shown in Fig. 1 as examples, as given by the DSS colored survey. Center coordinates for all clusters are shown in Table 1. The analyzed data is composed of UBV photometry cross-matched with Gaia DR2 parallaxes and proper motions. A small fraction of the processes applied by ASteCA on the data associated to each cluster are presented in Figs. 2, 3 and 4. The parallax data from Gaia DR2 is shifted by an offset of +0.029 mas, as suggested by Lindegren et al. (2018). More recent studies suggest that this offset might be too conservative, and larger values (up to +0.075 mas) have been suggested.

Table 1: Center coordinates for each cluster

Name	RA (2000)	DEC (2000)
RUP 41	07:53:51.81	-26:57:42.9
RUP42	07:57:38.88	-25:56:6.0
RUP44	07:58:54.00	-28:34:60.0
RUP152	07:54:30.48	-38:13:12.0
HAF14	07:44:49.20	-28:22:48.0

The structural density maps for RUP44 and HAF14 are shown in Fig. 2. This analysis is performed to help identify the center coordinates, and the radius used to limit the cluster region (green lines and green circle, respectively). About half of the clusters are immersed in regions of heavy field stars contamination, as can be seen in the density maps.

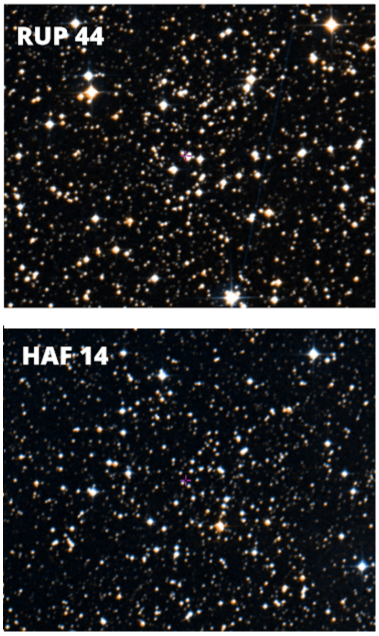

Figure 1: Frames for open clusters RUP44 and HAF14, located in the third quadrant of the Milky Way. Images obtained through the Aladin (CDS) service.

Table 2: Results obtained for the metallicity ([Fe/H]), age (log(age)), extinction (E_{BV}), distance modulus (dm), and mass (M in solar masses) for the five analyzed open clusters. For each quantity its mean value and standard deviation (in parenthesis, below) is reported.

Name	[Fe/H]	log(age)	E_{BV}	dm	M)
RUP41	0.16	8.63	0.28	13.71	200
	(0.10)	(0.20)	(0.02)	(0.14)	(100)
RUP42	-0.25	8.34	0.39	14.01	800
	(0.16)	(0.05)	(0.01)	(0.06)	(200)
RUP44	-0.22	7.21	0.69	13.33	700
	(0.09)	(0.02)	(0.01)	(0.06)	(100)
RUP152	-0.63	8.58	0.59	14.76	1800
	(0.27)	(0.02)	(0.01)	(0.11)	(100)
HAF14	-1.05	8.66	0.66	12.23	1100
	(0.38)	(0.03)	(0.01)	(0.05)	(100)

A Bayesian decontamination algorithm is applied over all the stars within this cluster region, to assign membership probabilities to all of them. This algorithm compares the color - magnitude (CMD) position of observed stars within the cluster region, with those of field stars in the same CMD. In this case we employ the V vs $(B-V)$ vs $(U-B)$ three dimensional CMD to perform this analysis. The colors in Fig. 3 and Fig. 4 for the plotted stars (ie: those within the cluster region) are associated to these probabilities.

In Fig. 3 we show the Bayesian parallax analysis proposed by Bailer-Jones (2015) on the cluster region stars. This analysis makes use of all stars, even those with negative parallax values of no apparent (physical) value. The distances obtained are heavily affected by the selected offset applied on the parallax, so they should be taken with care.

To estimate the fundamental parameters of the clusters, i.e.: metallicity, age, extinction, distance, and total mass, ASteCA generates synthetic clusters that are compared to the observed one. By means of a Bayesian MCMC algorithm, the analysis is performed millions of times to stimate the probability distribution of each parameter. The algorithm, called PTEMCEE (Vousden et al., 2016), is used to explore the posterior probability of all the free parameters involved in the model. Only the binary fraction parameter is fixed to 0.3, which is a commonly accepted value for open clusters (Sollima et al., 2010). As an example, Fig. 4 shows the result of this analysis for open clusters RUP44 and HAF14.

We find that all the analyzed clusters are younger than 500 million years, with metal content values that range from markedly sub-solar like HAF14, to slightly above solar in the case of RUP41. RUP44 is affected by the largest extinction, reaching almost the maximum value estimated by Schlafly & Finkbeiner (2011) of ~ 0.7 mag. It is also the youngest cluster of the sample.

Table 2 summarizes the results obtained for the fundamental parameters of all the studied clusters. There are appreciable differences in the distances estimated by Gaia parallax versus ASteCA's photometric analysis. The difference between the Gaia and the ASteCA

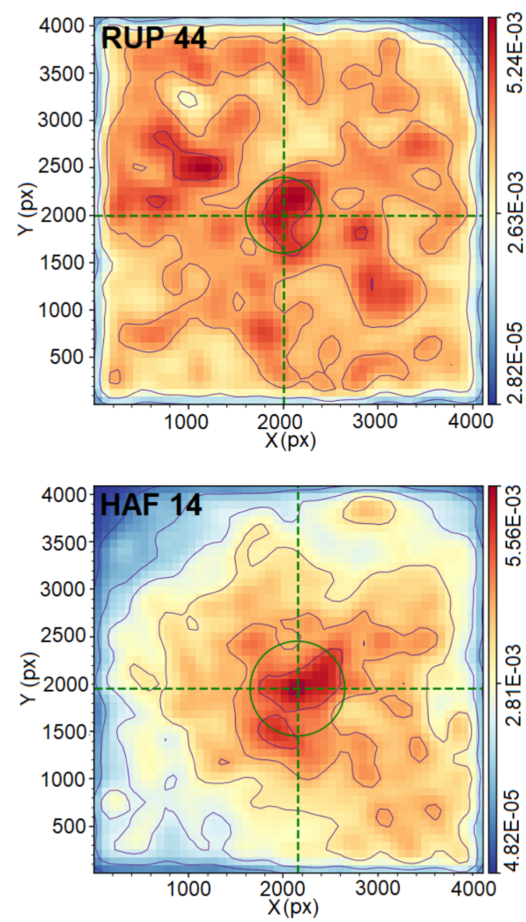

Figure 2: Structural density maps for open clusters RUP44 and HAF14. The color bars to the right are associated with the stellar density in the field.

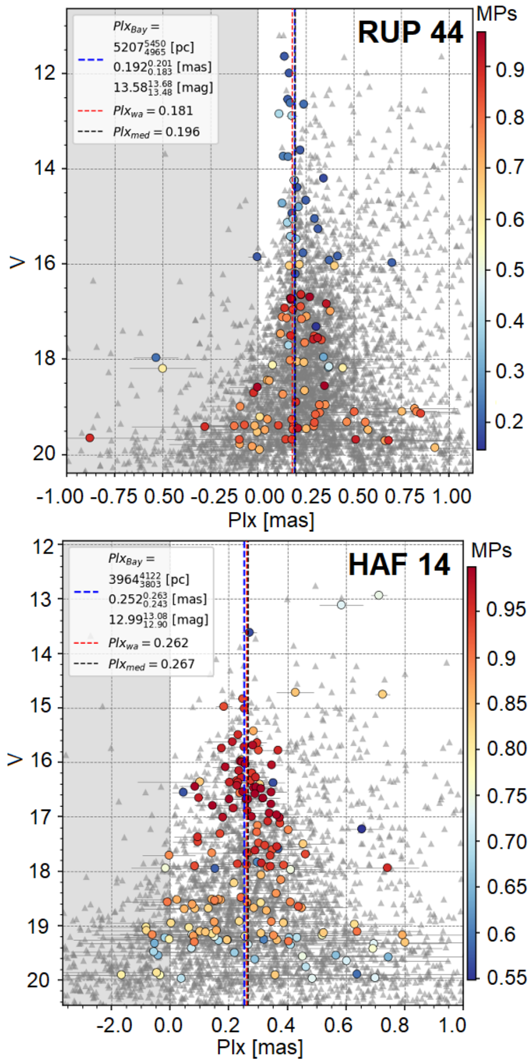

Figure 3: Bayesian parallax analysis for open clusters RUP44 and HAF14. The dashed vertical lines represent the Bayesian distance obtained (blue), the weighted average of the parallaxes (red), and the median of the parallaxes (black). The color bars indicate the membership probability.

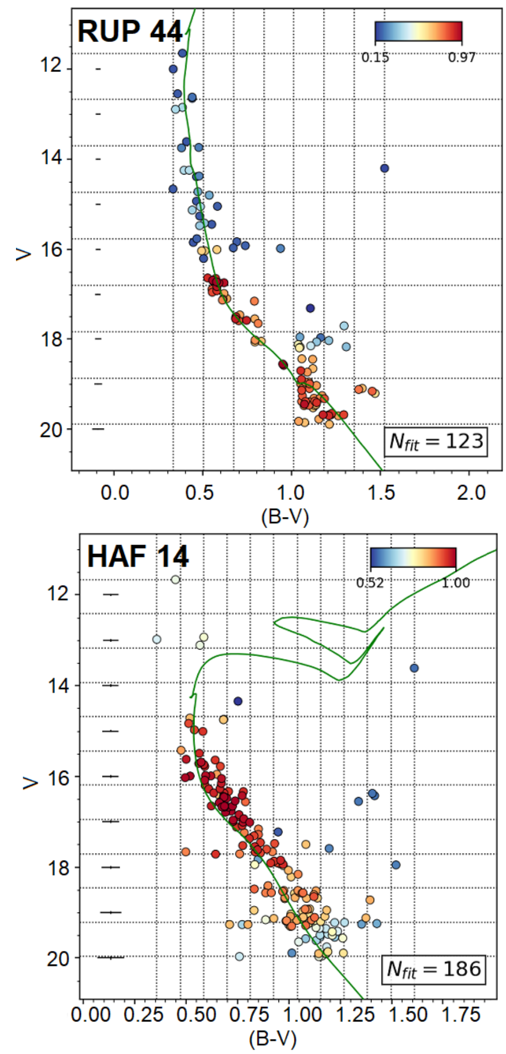

Figure 4: Data points (color circles) for clusters RUP44 and HAF14, and the isochrone (in green) used to generate the best synthetic fit. In each case N_{fit} indicates the number of stars used in the fitting process.

based estimates are: RUP41 ≈ -1.5 kpc, RUP42 ≈ -0.8 kpc, RUP44 ≈ 0.6 kpc, HAF14 ≈ 1.2 kpc, RUP152 ≈ -1.8 kpc.

3. Conclusions

The results of applying ASTECA over the combined UBV+G (Johnson-Kron-Cousin plus Gaia systems) photometric data are very promising. Due to the Bayesian inference method recently implemented, the code is able to find reasonable solutions for all the parameters of each analyzed cluster (Table 2). Upcoming versions of ASTECA will aim at improving its computational time performance.

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