Study of HR diagrams using Gaia data

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ABSTRACT

Aims. In first place the aim of this work is to find the age and metallicity of different stellar populations. In our case, the *Hyades* and the *47 Tucanae*.
Methods. To do this we'll be constructiong different HR isocrone diagrams and comparing them with HR diagrams from Gaia data in the regions where we know these two stellar populations are. The construction of the first diagrams will be performed using a software held by Léo Girardi⋆, which models isochrones for different metallicities and ages. The second ones will be downloaded directly from Gaia using ADQL.
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Key words. HR Diagram – Hyades – 47 Tucanae – Metallicity – Age

1. Introduction

The Hertzsprung-Russell diagram (HRD) is a frequently used tool in astrophysics since their development in the last century. This diagrams consist of a vertical axis representing the luminosity of stars (that usually is presented as absolute magnitude) against temperature of these stars in the horizontal axis (that is presented as a color index in observational HRDs). This horizontal axis is normally flipped so the hottest stars are on the left section of the diagram.

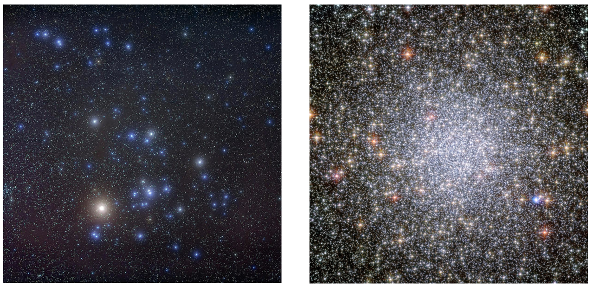
This diagrams aim to be a very useful tool to characterize stellar clusters, which are large populations of stars that have the same origin and star formation history and have been gravitationally bound, at least in some period of their lives. There are mainly two types of stellar clusters, Open clusters and Globular clusters. Globular clusters are tight groups of stars ($\sim 10^8$ stars) that are gravitationally bounded, Open Clusters on the other hand are less compact and have around a hundred stars or less.

For the realization of this work we will focus on one cluster of each type, we will analyze the Hyades as an Open Cluster and 47 Tucanae as a Globular Cluster (see Figure 1, Table 1). Both of them are well known Local Group clusters close to the Milky Way.

Table 1. Parameters of Hyades and 47 Tucanae.

	R.A (2000)	Dec (2000)	d (kpc)	R (pc)
Hyades	04:27:00	15:52:12	0.047	2.7
47 Tuc	00:24:06	-72:04:53	4±0.35	18.4

For the study of these stellar populations we'll be using isochrone fitting. These isochrones are representations in the HR observational diagram (which is presented as absolute magnitude versus a color index) that follow the course of the life of a star at different masses. These isochrones are observed when acquiring data from stellar clusters because all stars in these clusters have approximately the same age and stellar formation history, as well as metallicity. These two parameters, age and metallicity will we the targets of our study.



(a) **(b)**

Fig. 1. Hyades and 47 Tucanae clusters.

For the study we will first make an HR diagram using Gaia data on the region of both clusters, to get the real data isochrones. Then, we will create synthetic PARSEC isochrones, with a software developed by Léo Girardi[1], in which we can select a variety of parameters of stellar populations, like age and metallicity among other things.

The comparison between these two diagrams will end in a characterization of the physical properties of these clusters once we find the best matching isochrones for both clusters.

[1] A web interface dealing with stellar isochrones and their derivatives: http://stev.oapd.inaf.it/cgi-bin/cmd (From *Osservatorio Astronomico di Padova.*)

2. Methodology

For this section of the work we will start by making HR diagrams of the different regions of the sky regarding both the Hyades and 47 Tucanae clusters, as well as a generic sun surroundings HR diagram. Then, we will make some corrections on the HR diagrams to make sure every star presented on the diagram is a cluster member. Once we have the real data diagrams we will compute different isochrones with different metallicity and age values until we find the best fit for both clusters.

2.1. HR diagrams using Gaia data

We will start by acquiring the Gaia data to make the HR diagrams. This data will correspond to the latest data release from Gaia, which is *edr3* for the moment. To do this we will use TOPCAT with its cone search tool. Knowing the coordinates of the different clusters and their radius can give us a first approximation of the real cluster data. Once we have this data we can make an HR diagram for each cluster. To have a wider understanding of HR diagram making we started by making a HR diagram of stars in the Sun surroundings, this has a much larger number of stars than both clusters and the distribution doesn't really follow isochrones, as expected for non-bound stellar populations.

2.1.1. HR diagram for Sun surroundings

Firstly we will show the process of making the HR diagram for a Sun surroundings stellar population. For this we will be using the TOPCAT's ADQL tool and set the parallax of these stars to a minimum of 10 arcseconds, which will set a maximum distance to the stars. The raw HR diagram output when acquiring this data and representing it with TOPCAT is shown in Figure 2. Where we have flipped the vertical axis as it is normally done in HR diagrams.

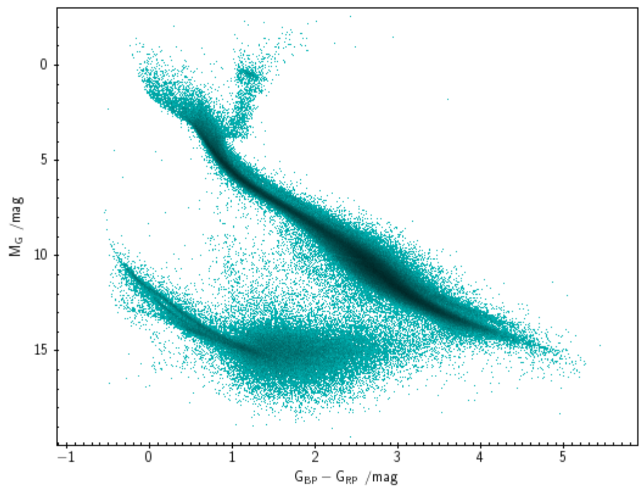
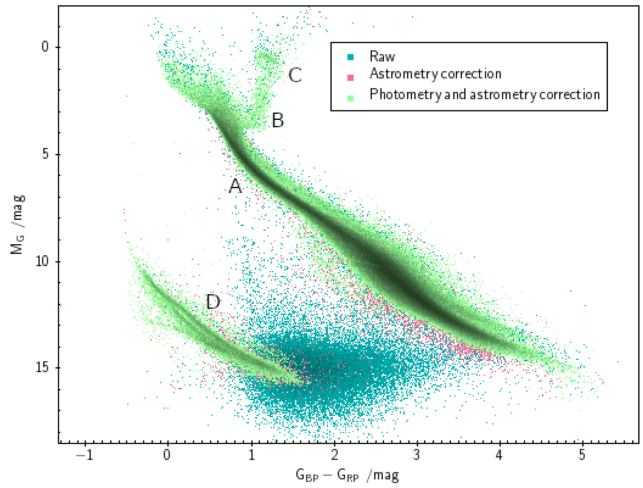
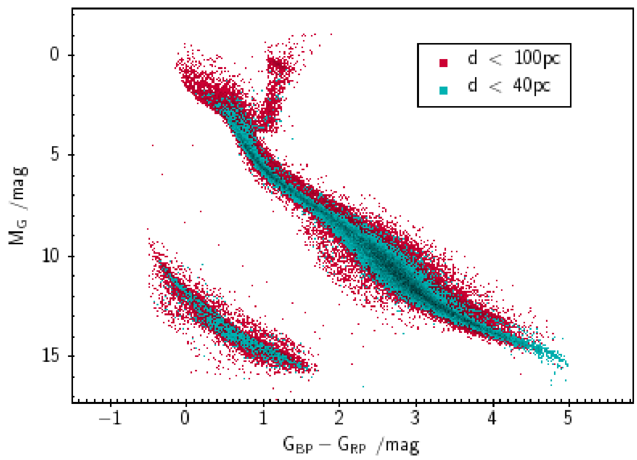


Fig. 2. HR diagram of Sun surrounding stars with Gaia data.

Now that we have our raw HR diagram we can clean it by taking in account the astrometry and photometry errors. For doing this we will use TOPCAT and we will set the astrometric_excess_noise to accept only values lower than 1. Then we'll be correcting the photometry by using the polygon selection tool on the parameter phot_bp_rp_excess_factor, only choosing the most overdense region that has a maximum value at around 1.5. The fully corrected diagram is shown in Figure 3a. In it we can clearly see the 4 main structures of an HR diagram: **A** - Main Sequence, **B** - Red Giant Branch (RGB), **C** - Red Clump, **D** - White Dwarfs.



(a)



(b)

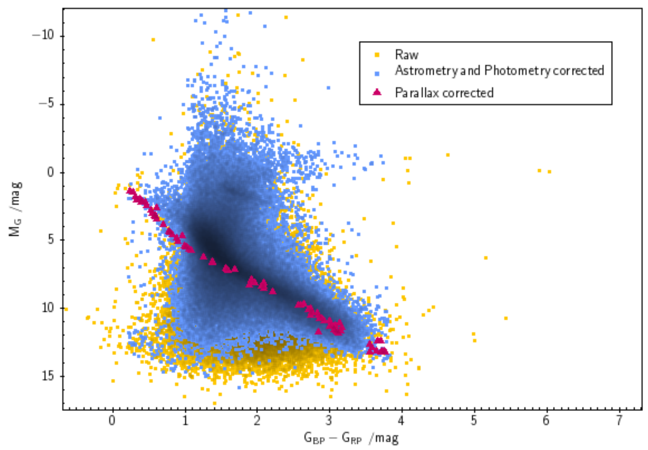
Fig. 3. HR diagram of the Sun surroundings. In (a) we can see the different corrections applied to the raw Gaia data and in (b) different distances from the Sun were used to see the behavior of the HR diagram depending on the distance.

As we see in Figure 3b, as the distance is larger, the HR diagram experiments a widening, this is caused by a higher range of metallicities in the sources, as well as a larger sample of binary systems, that tend to be brighter than normal stars for the same magnitude.

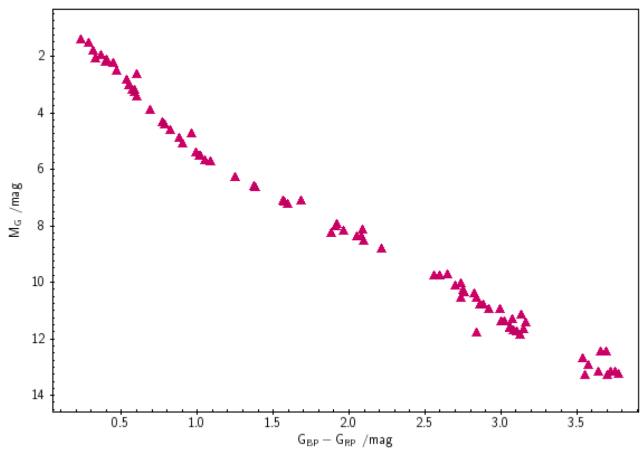
2.1.2. HR diagram for Hyades cluster

Now that we have understood the methodology of HR diagram making we can continue with the Hyades cluster. As we know the coordinates of both clusters (see Table 1) we can use Gaia's tool cone-search to place a cone projection on the sky where the coordinates are and knowing the distance from the Sun to the cluster and the radius of it, estimate an angle for the cone to gather all the cluster members.

For this first cluster we will make a `cone-search` around the coordinates with an angle of 3.29°. As we explained for the sun surroundings HR diagrams, we will clean the values by setting some boundaries in the photometric and astrometric errors. These will we taking in account and are presented in Figure 4. In this Figure we can also see a final sample, in dark red (see Figure 4b). This last parallax correction is to make sure the distance of each source lays on the distance of the cluster. To do so we simply applied boundaries to the distance. The criteria was simple, we took the distance to the center of the cluster and allowed a range set by the radius of the cluster, that was approximately 3pc. This let us to the final boundaries: d= 47 ± 3 pc, which let a sample of 81 sources that is very close to the real number of sources in Hyades cluster.



(a)



(b)

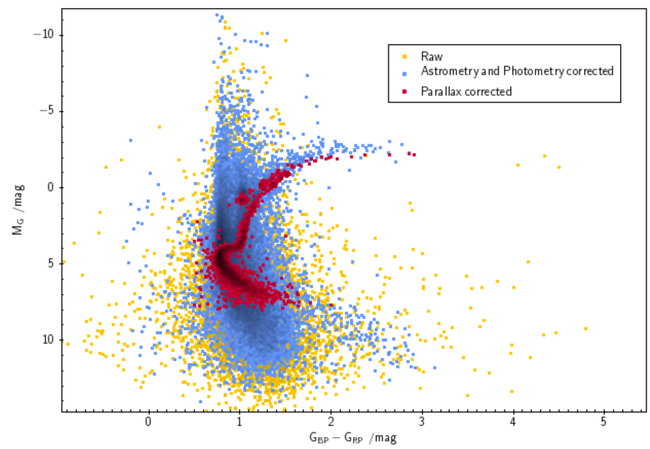
Fig. 4. HR diagram of the Hyades cluster. In (a) it is represented the raw Gaia data from the sky region in yellow and the photometric and astrometric corrections in blue, as well as the final parallax corrected sample in dark red. In (b) we can see the final fully corrected sample isolated.

As we can see, the final sample of sources are following the course of what could be a main sequence inside the HR diagram, for what we are satisfied with the results.

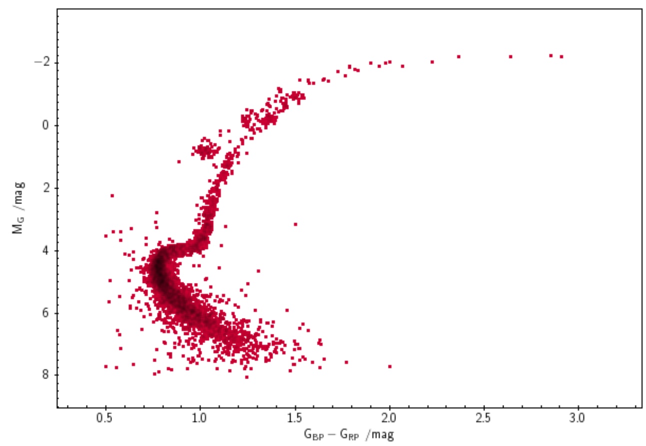
2.1.3. HR diagram for 47 Tucanae cluster

Lastly, we can make the HR diagram for 47 Tucanae cluster following the same steps we followed for the Hyades cluster. In first place we will use Gaia's cone-search in ADQL again, but this time we will have a different angle measurement (being that the ratio between radius of the cluster and its distance from the sun is much lower). For 47 Tucanae we will make a cone search of 0.26°width.

Remember that 47 Tucanae is a globular cluster, which has a much larger population of stars, so we will expect to have much more sources in this query, even after all the corrections. The raw HR diagram for 47 Tucanae can be found at Figure 5a, together with the final sample of sources in Figure 5b. For the final parallax correction this time we used the boundaries: d= 4000 ± 35 pc.



(a)



(b)

Fig. 5. HR diagram of the 47 Tucanae cluster. In (a) it is represented the raw Gaia data from the sky region in yellow and the photometric and astrometric corrections in blue, as well as the final parallax corrected sample in dark red. In (b) we can see the final fully corrected sample isolated.

As we did on the Sun surroundings HR diagram, we can also identify the different parts of the diagram for the 47 Tucanae one (see Figure 6). For this case: **A** - Main Sequence, **B** - Turn off point , **C** - Red Giant Branch (RGB), **D** - Horizontal Branch , **E** - Asymptotic Giant Branch (AGB).

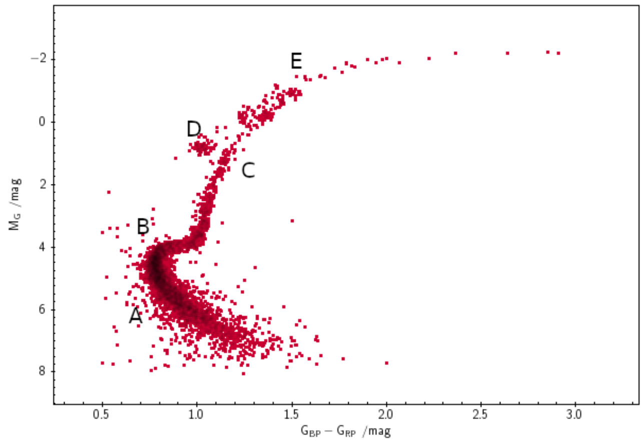


Fig. 6. HR diagram of 47 Tucanae with indicated parts.

The identifications of the different phases tells us various characteristics of the cluster. The first one is that it is older than the Hyades cluster, as it has stars beyond the Main Sequence. The other thing is that the number of cluster members is massive in comparison with the Hyades cluster.

2.2. Isochrone Fitting using PARSEC isochrones

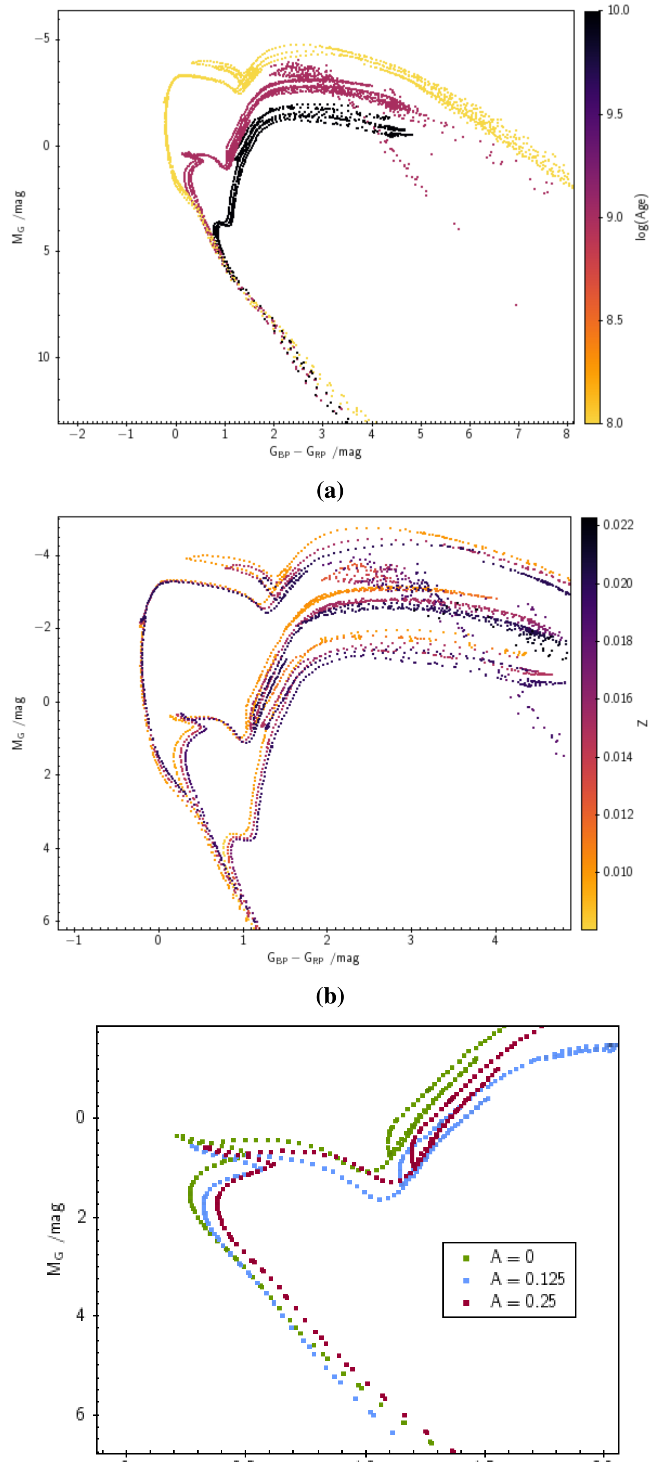
For this second part of the section we will adjust the different resultant HR diagrams with synthetic isochrones created using PARSEC isochrones[2].

To have a first orientation of the isochrones behavior, we can plot 3 groups of ages and 3 subgroups of metallicities for the same ages, as well as a generic graph of different extinction values. This three figures are represented in Figure 7. In Figure 7a we can clearly see how the different ages behave, as we go to larger ages, the turn off point will go to redder and colder regions of the diagram, as well as to brighter regions, but the principal shift is in the vertical axis. For the metallicities we can take a look at Figure 7b, where for the same ages, different metallicities will shift the isochrone horizontally, for higher metallicities the isochrone will shift to the left whereas for lower metallicities the isochrone will shift to the right.

With this in mind, we can develop a plan to find the best isochrone fit for our cluster HR diagrams. At first we will try to find the fit to the age of the cluster, which is closely linked to the position of the turn off point and it has a bigger impact in the shape of the isochrone. Once we have achieved a good age fit we can then try different metallicites to adjust the isochrone better.

Another important parameter to have in mind is the extinction, which is the absorption of the gamma radiation from the inter-galactic medium. This can really affect the observation of different isochrones, letting to important changes in the shapes of these. As we can see in Figure 7c, the extinction plays an important role shifting the isochrone to the colder part of the diagram for higher extinction values.

[2] A web interface dealing with stellar isochrones and their derivatives: http://stev.oapd.inaf.it/cgi-bin/cmd



(a)

(b)

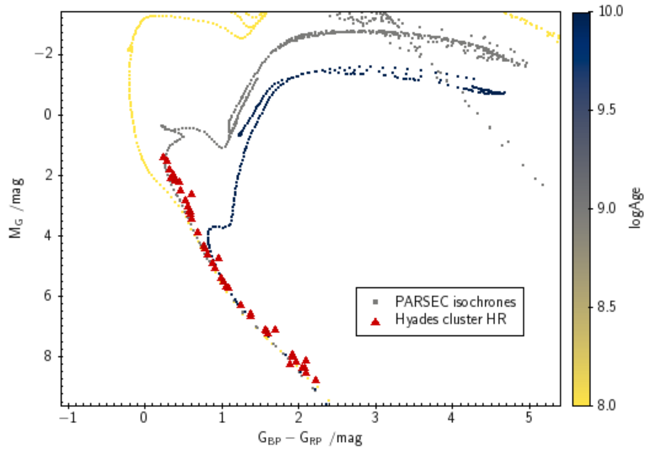
(c)

Fig. 7. PARSEC isochrones for different ages and metallicites. This figures shows the behavior when changing the metallicity or the age of any stellar population.

2.2.1. Isochrone Fitting for Hyades cluster

As we are starting with the Hyades cluster, we know it is an open cluster, which tend to be young, approximately at about a few hundred million years ($\sim 10^8$ yrs). So, we can start by setting our metallicity to Z=0.015 and set a range of ages between 10^8 and 10^{10} years (see Figure 8a). Once we do this we can quickly see how the better fitting age is around log(Age)≈9, so now we can make new isochrones narrowing down the values.

Now we can see that the curve that fits best between the different PARSEC isochrones is the one with log(Age)≈8.9 (see Figure 8b). Focusing on the age and trying for different metallicities the best fit was found at Z=0.02 (see Figure 8c).



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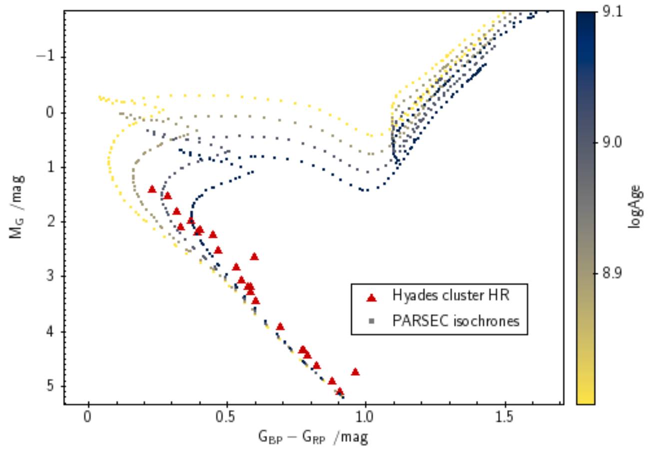

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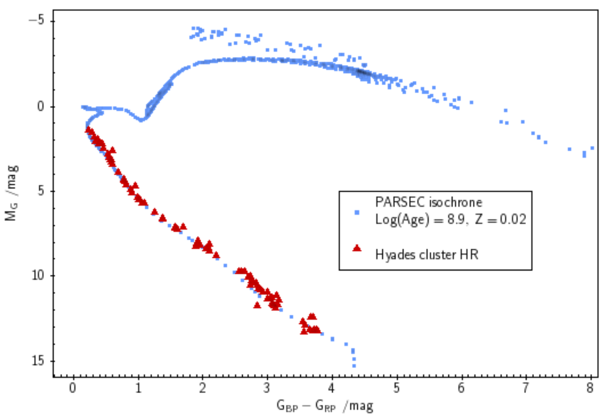
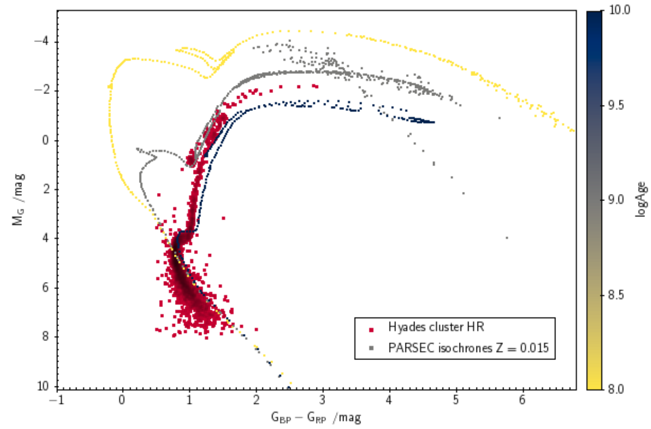


(c)

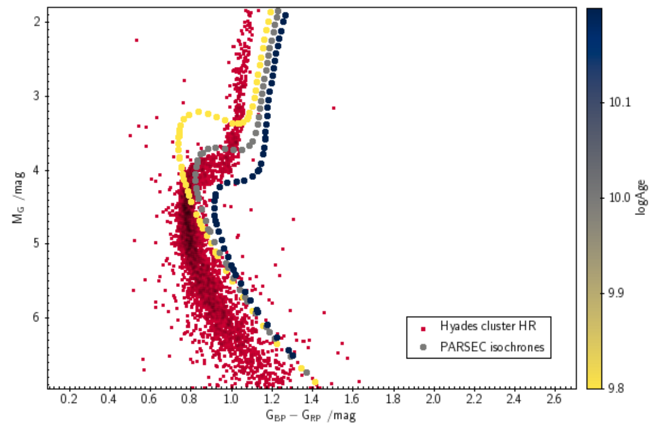
Fig. 8. PARSEC isochrone fitting for Hyades cluster in 3 steps.

2.2.2. Isochrone Fitting for 47 Tucanae cluster

The process for 47 Tucanae will be the same as for the Hyades cluster. First we will focus on an age range between 8<log(Age)<10 and a fixed metallicity of Z=0.015 (see Figure 9a). With this comparison we realized that the best fitting isochrone must be around log(Age)≈10.



(a)



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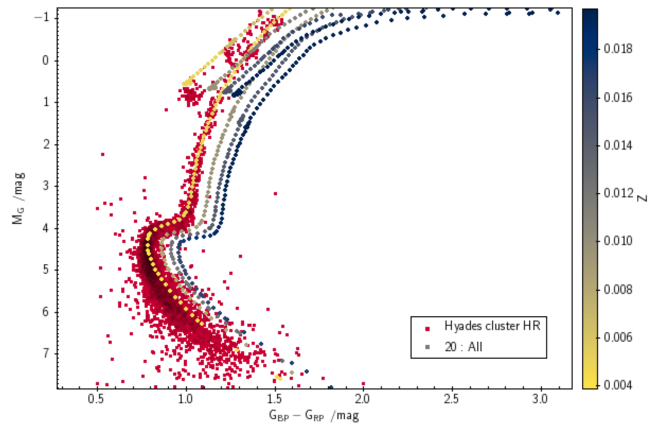

(c)

Fig. 9. PARSEC isochrone fitting for 47 Tucanae cluster in 3 steps.

In the next step we use a narrower range of ages, 9.8<log(Age)<10.2, focusing on the behavior we saw in the previous step. We can clearly see how the shape of the log(Age)=10.2 isochrone is the most similar to the HR curve behavior at the turn off point. As the other curves are peakier and this one is shallower. (see Figure 9b).

Finally, focusing on this age, we can move to the metallicity, where we placed a big range of values, clearly finding the best fit at Z=0.005. (see Figure 9c).

3. Results

In this section we will present the final results of the metallicites and ages found for both clusters, the Hyades and 47 Tucanae. We will also explain the results found when making HR diagrams of the Sun surroundings at different distances.

3.1. HR diagram of Sun surroundings at different distances

Back in the methodology section, we plotted the HR diagram for Sun surroundings at different distances, knowing that for larger distances, a wider metallicity range will widen the Main Sequence and the HR diagram in general. Also the presence of more binary systems will play an important role ion the widening.

Even so, distances lower than 40pc are very low having in mind that the Sun is at 8kpc from the center of the galaxy. Also, using a maximum boundary will not give us much information beyond the fact that when we go closer there will obviously be less number of detected sources. Having this in mind, we can look for different distance ranges to look at the behaviour of the Gaia data. This is what we did in Figure 10.

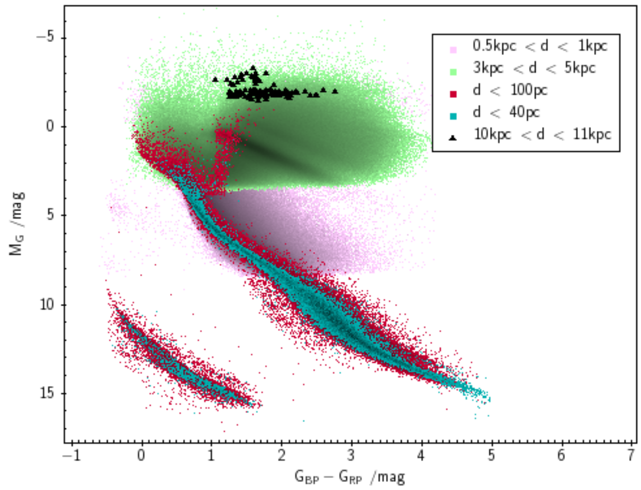

Fig. 10. HR diagram of Sun surroundings at different distances.

This is a very interesting plot in which we can clearly see how for higher distances the Supergiant branch appears. This is because for larger distances, only the brightest stars will reach Gaia's detectors and will make it to the HR diagram. In fact, we can clearly see how for different distances there is a clear lower threshold that sets the minimum brightness (maximum magnitude) for a star emission to reach Gaia.

We also plotted an extreme case at 10 to 11 kpc, which is represented by plain black triangles in the diagram. We can see as it is de farthest sample of all in the diagram, it is the brightest one also. The sample is also very small in comparison with the others, we can assume that this is caused by the reach of Gaia's detections, which can't be infinite, but it could also be caused by the central galaxy bulge that is contaminating the data, being the distance of this sources is larger than the distance from the Sun to the center of the galaxy.

3.2. Age & metallicity of 47 Tucanae Cluster

For 47 Tucanae cluster the results obtained by the PARSEC isochrone fitting where the one shown in Figure 11.

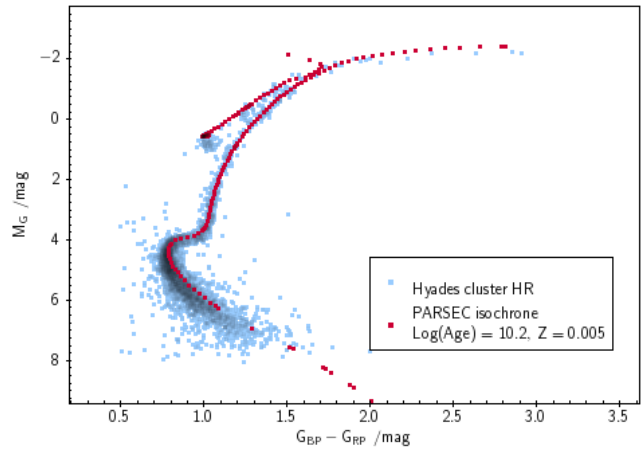

Fig. 11. Final PARSEC isochrone fitting for 47 Tucanae cluster.

The final **results for 47 Tucanae cluster** are: **log(Age)=10.2** and **Z=0.005**.

3.3. Age & metallicity of Hyades Cluster

For Hyades cluster the results obtained by the PARSEC isochrone fitting where the one shown in Figure 12.

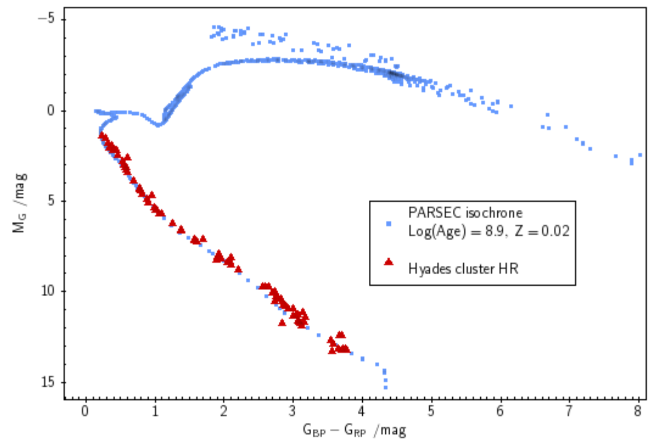

Fig. 12. Final PARSEC isochrone fitting for Hyades cluster.

The final **results for Hyades cluster** are: **log(Age)=8.9** and **Z=0.02**.

4. Discussion & conclussions

The first thing to consider is the scattering happening in the HR diagrams of the two clusters. This can be caused by various things, as we mentioned above, one of them could be the presence of binary systems that widen the diagram. Other cause might be the resolution of the data, which can be worse at larger distances, which is normal to happen more for the 47 Tucanae cluster.

Even so, the results and the fitting of the different isochrones seem very promising and correct for the purpose of the work. We can also make a quick comparison of the results with the bibliography to confirm that the values lay on the expected range.

Comparing with Lastennet ((1999)), they obtained a value for the age of the Hyades cluster of log(Age)≈8.85, which is very close to our results. For the 47 Tucanae cluster, looking at Bergbusch and Stetson ((2009)) they present an age of 12Gyrs, whereas we obtained 15.8Gyrs, which is an acceptable result.

A Conclusions we can affirm that:

- We managed to download gaia data for different regions of the sky, learning to use ADQL code.
- We represented this Gaia data with `TOPCAT`, learning also how to use the software.
- PARSEC Isochrone fitting let us to very acceptable final results for both clusters, determining successfully their ages and metallicities.

References

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