Universidad de La Laguna

MÁSTER DE ASTROFÍSICA

Técnicas Computacionales Básicas

Starmap and proper motions over time

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Contents

1 Introduction

Deep space is a very complex environment to study, as we human beings have many limitations when it comes to making direct measurements of it. That is why the best way to analyse this environment is through indirect methods, specifically by analysing the light that reaches us from the different astronomical bodies and physical systems that compose it, which is the basis of practically all research works that have been done in astrophysics.

Specifically, stars are one of the astronomical bodies that allow us to obtain most information about the functioning of the Universe and its constitution. Thanks to the development of different techniques such as astrometry, which allows the analysis of the proper motions, parallaxes and positions of stars, or photometry, which allows the analysis of their brightness, we have a tangible capacity to carry out a quality study of the different stellar structures that can be observed in the sky.

Following the desire to obtain the largest three-dimensional spatial catalogue to date, the European Space Agency (ESA) launched the Gaia space mission in 2013 (Prusti (2016)). This probe aims to build a catalogue for a total of 2 billion astronomical objects, including not only stars, but also planets, comets and quasars, among other astronomical objects. For years, Gaia has been obtaining measurements of these objects and has been able to build a database on them (European Space Agency (ESA) (2024)). One of the main objectives of this mission is to improve the precision of the measurements as well, especially compared to the previous Hipparcos mission (ESA (European Space Agency) (1997)), also from ESA. Not in vain, astrometric measurements of parallax are usually associated with a greater error as the observed objects are located farther away from the observer.

Over the years that the satellite has been in operation, a number of measurements have been released. For the first data release, positions, parallaxes and proper motions of two and a half million stars were provided, in common with the Hipparcos and Tycho-2 catalogues (Collaboration (2016)). The second Gaia data release (Gaia DR2) obtained the same measurements for a total of 1.3 billion stars, and improved the astrometric precision of its predecessor Hipparcos (Gaia Collaboration (2018)). Finally, the third Gaia data release (Gaia DR3) (Gaia Collaboration (2022b)), has provided a better precision for the measurements, improving the uncertainties of the proper motions by a factor of 0.5 and the uncertainties of the parallaxes and positions by a factor of 0.8 (L. Lindegren (2021)). It has also allowed a new characterization of the stars in terms of their effective temperatures, surface gravity, metallicity, etc (O. L. Creevey (2023)). All these astrometric data have been very useful for carrying out different works. An example of this could be the study of the proper motions of OB stars in the Carina Arm, to characterize possible significant stellar ejections over that part of our galaxy (J. E. Drew (2021)).

In this context, it is particularly relevant to analyze the data from the Gaia and Hipparcos astronomical satellites in order to specifically study how Gaia has significantly expanded our star catalogs in the vicinity of our solar system. To do so, in this work we select all the stars from the catalogs of both probes and we keep the brightest ones (with apparent magnitude less than 10) that we can observe in the northern hemisphere (with positive declination). We also select an area of the sky and study the stellar density maps, which is relevant in our effort to identify clusters or other similar structures in the Milky Way. Finally, we are interested in making a temporal analysis based on the proper motions of the stars, that is, the movements that the stars follow in the plane of the sky, which can allow us to make estimations about how the stars in our map will evolve at different future moments in the order of tens of thousands of years, until obtaining a prediction of how the stars in our sky will be distributed within 100,000 years.

2 Methodology

As we have already mentioned in section 1. To elaborate our own starmap using *python*, we are going to take data from two important catalogues: Gaia and Hipparcos.

2.1 Catalogue comparison

In order to do this, a query was made with *astroquery.gaia* and *astroquery.vizier* modules (Astroquery Collaboration, 2024a) (Astroquery Collaboration, 2024b). The last one allows us to access several catalogues, among them Hipparcos.

The query was made with several constraints: that the stars are brighter than 10 magnitude and that their declination is greater than 0 degrees, therefore, stars that are in the northern hemisphere.

Before starting to process the data, we compare the two catalogues in terms of the amount of output data each provides, as well as the magnitude, distance distributions, and their uncertainties. This allows us to see which of the two is more complete and more suitable for our purpose. In addition, a cross-identification was made to see the number of repeated stars between the two catalogues. This allows us to see if one set is contained in the other or if they complement each other.

Once the above results are obtained, the data from one or the other catalogue or a combination of both are used depending on the result obtained.

2.2 Starmap development

After this selection, we move on to processing the data to produce our own starmap. Due to the large number of stars, it is necessary to filter the stars by some additional constraint. Otherwise, the map will not be clear and legible enough. There are several constraints that could be taken, such as eliminating stars by defining a limit to the parallax or proper motion errors. Nevertheless, to keep as many stars as possible, we filter the stars by magnitude. We plot the brightest stars by points and put the more distant and less bright stars as a background density map. This way of representing our starmap was inspired by the Tirion (2024) maps. As there are still a large number of stars, only a portion of the sky was taken, limiting the right ascension range.

To take the centre of the limit of the right ascension we have taken as a reference the sidereal time in Tenerife, using the *astropy.time* module (The Astropy Collaboration, 2024a) as you can see in our code (Lucia, Angeles, Moises and Carlos, 2024). With this module it would be possible to transform to horizontal coordinates (altitude and azimuth The Astropy Collaboration (2024b)) and find the stars visible at that time. But in our case, we have only restricted the range of right ascension and keeping a declination from 0 to 90 degrees restricting us to only a part of the sky. Then, only by changing the right ascension range we can capture the whole sky with that declination.

Moreover, the constellations were also identified by a colour legend for the subsequent time evolution. For this purpose a function was defined that identifies the constellations by the declination and right ascension of a star. That is to say, given a right ascension and declination, it associates it with a constellation that is included in a list created with some of the most important constellations. If the resultant constellation is not included in the list it returns *None*. This function uses *get-constellation()* from The Astropy Collaboration (2024c).

We have defined this function to be maintained over time evolution so that we can see more clearly how stars move from these points over time.

2.3 Starmap evolution

With our current starmap done, we can make a time evolution of how the stars will look like in the future. This is possible by using the proper motion values in declination and right ascension of the catalogues. These are in mas/yr units. Then, with a simple transformation from mas to degrees and a time interval of 10000 years we can add how much each star has moved to the current right ascension and declination. With that we will be able to predict its position in the future. This is easily done by using a *for* loop that runs through all the star values in our starmap adding 10000 years at each iteration.

The evolution was done for until 200000 year, taking into account that we are currently at approximately 100000 years. Also, as a curiosity, by how the code was programmed, it is possible to make a time regression.

3 Results & Discussion

3.1 Catalogue selection and distributions

First we construct the queries to extract the data from the catalogues. As can be seen in the code, the catalogues were cleaned, eliminating possible NaNs and negative parallaxes after the queries were executed. As a result, Gaia gave us a total of 225755 stars, while Hipparcos gave us 49 stars. With this data we can proceed to make the different distributions of both catalogues, like it can be seen in Figure 1 and Figure 2. As the Gaia values went up to high values of *kpc* compared to Hipparcos we restricted them to the highest value of Hipparcos, up to 2500 pc. Therefore, we now have 222900 Gaia stars. It can be seen in the first figure that in terms of number of stars and apparent magnitude distribution the Gaia catalogue is much more complete. Since the apparent magnitude range of Hipparcos is from 10 to almost 6 with a peak of 7 stars between 9 and 8 magnitude. However, in the Gaia case the range goes from 10 to 2 magnitude (is quite tiny to see in the histogram) with a peak of 50000 stars in the 10 magnitude. And approximately between 9 and 8 magnitude (where there is a peak in hipparcos), it has around 10000 stars.

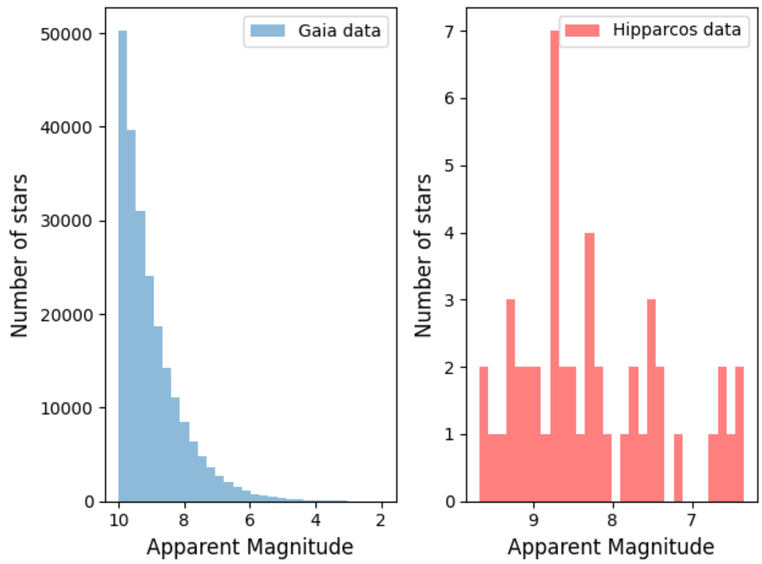

Figure 1: In blue the apparent magnitude distribution of Gaia data. In red the distribution of the Hipparcos data.

The same happens in Figure 2 with the distance, where Hipparcos shows a gap between $1kpc$ to $2.5kpc$. In addition, Figure 3 and Figure 4 show the distance distribution with their uncertainties. In order to find the uncertainties in the distances, an error propagation of the parallax-to-distance transformation had to be done.

$$\Delta d = \frac{\Delta p}{p^2}, \tag{1}$$

where d is the distance in pc Δd the uncertainty in the distance, p is the parallax and Δp is the uncertainty in the parallax.

As the figures show, the error rate in the Gaia distribution of distances is much smaller than that of Hipparcos, even taking into account its larger number of stars.

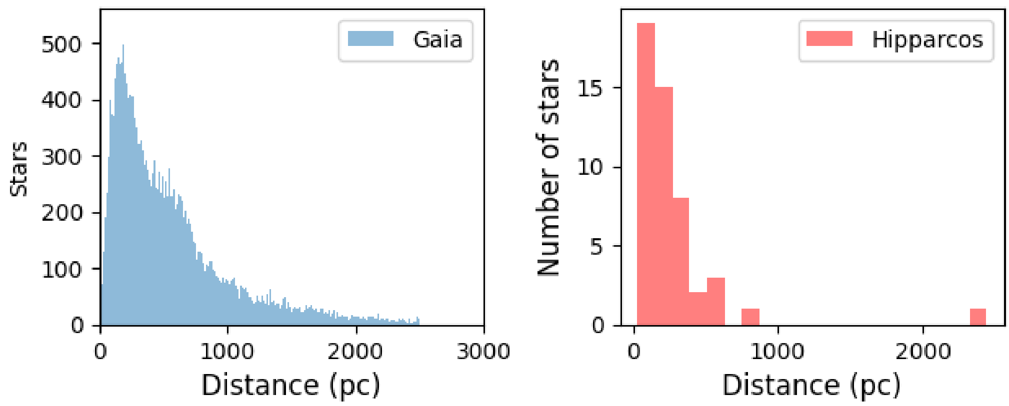

Figure 2: In blue the distance in pc distribution of Gaia data. In red the same distribution for the Hipparcos data

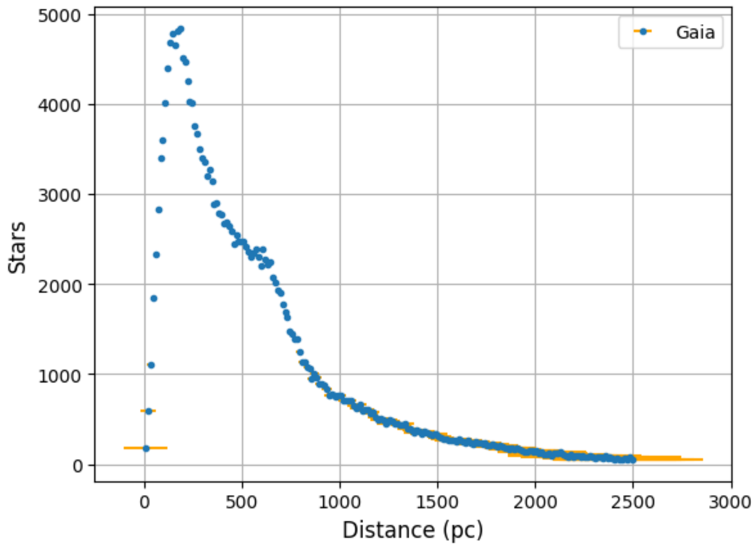

Figure 3: The distance distribution of Gaia data. The blue points represent a set of stars and orange bar the error bar in the distance. This error is given by the query.

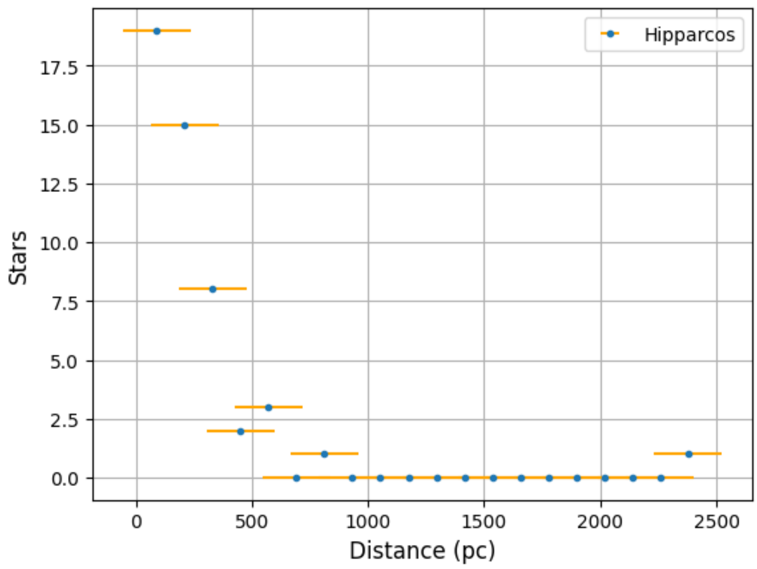

Figure 4: The distance distribution of Hipparcos data. The blue points represent a set of stars and the orange bars the error bars in the distance. This error is given by the query.

3.1.1 Catalogue Cross-identification

In the cross-identification, we make use of different Astropy modules such as: *astropy.coordinates* and *astropy.table* (The Astropy Collaboration, 2024d,e). By filtering the matches with a threshold of 1 *as* a match of 15 stars was obtained. With the results of the catalogue longitude, the distributions and coincident stars by cross-identification, we have taken the decision to use only the Gaia catalogue data. Especially because of its large sample of stars with a variety of distances, magnitudes and a large ratio of values and uncertainties. And even if there are only 15 coincident stars between the Gaia and Hipparcos catalogues (it is possible that we have been too strict with the threshold) and it cannot be stated that the Gaia catalogue contains the Hipparcos catalogue, the resulting ratio would be Gaia with 222885 stars and Hipparcos with 34 stars. So the addition of these stars to the large Gaia catalogue would not make a big difference, especially since the peak magnitudes of Hipparcos are between 9-8 magnitude, which are relatively faint brightnesses.

3.2 Starmap of the current sky

As discussed in subsection 2.2 on how the starmap was constructed and shaped, we have a large amount of data (222900 stars) so, we proceeded to do a magnitude filtering by removing those below 9. However, the number of stars was still large enough to clearly discern the stars. It was then restricted to a part of the sky, with a right ascension range of 80-260 degrees and keeping a declination of 0 to 90 degrees. This can be changed at any time in our code (Lucia, Angeles, Moises and Carlos, 2024), which would not affect subsequent processes but would adapt to the change. The Figure 5 and Figure 6 show The current starmap with and without highlighting the constellations respectively. There are a lot of stars represented in the two figures. In the following starmaps, for clarity, we are going to represent with points only until 6 magnitude. The more distant ones are going to be in the density map of the background because the representation with all magnitudes and constellations makes the map look overloaded.

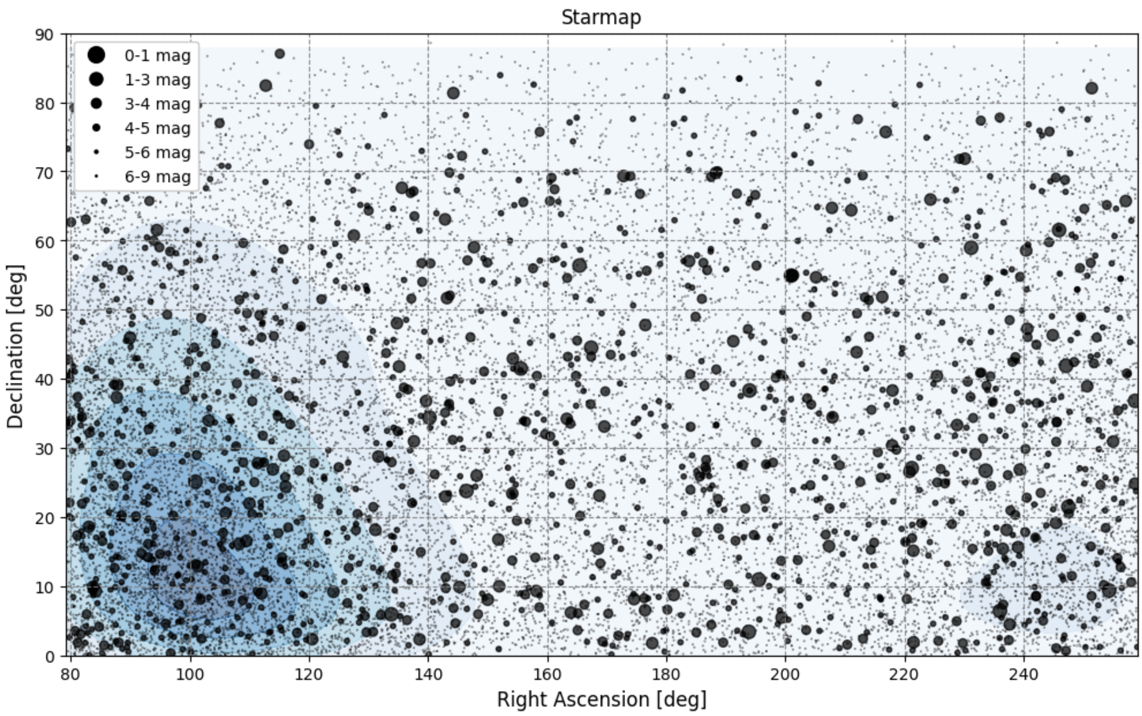

Figure 5: Starmap represented with declination and right ascension. The points and circles represent the stars in the sky and their sizes depends on their magnitude. The blue background density contour represents the more distant and faint stars. At more than $1kpc$ and with an 8.5 magnitude

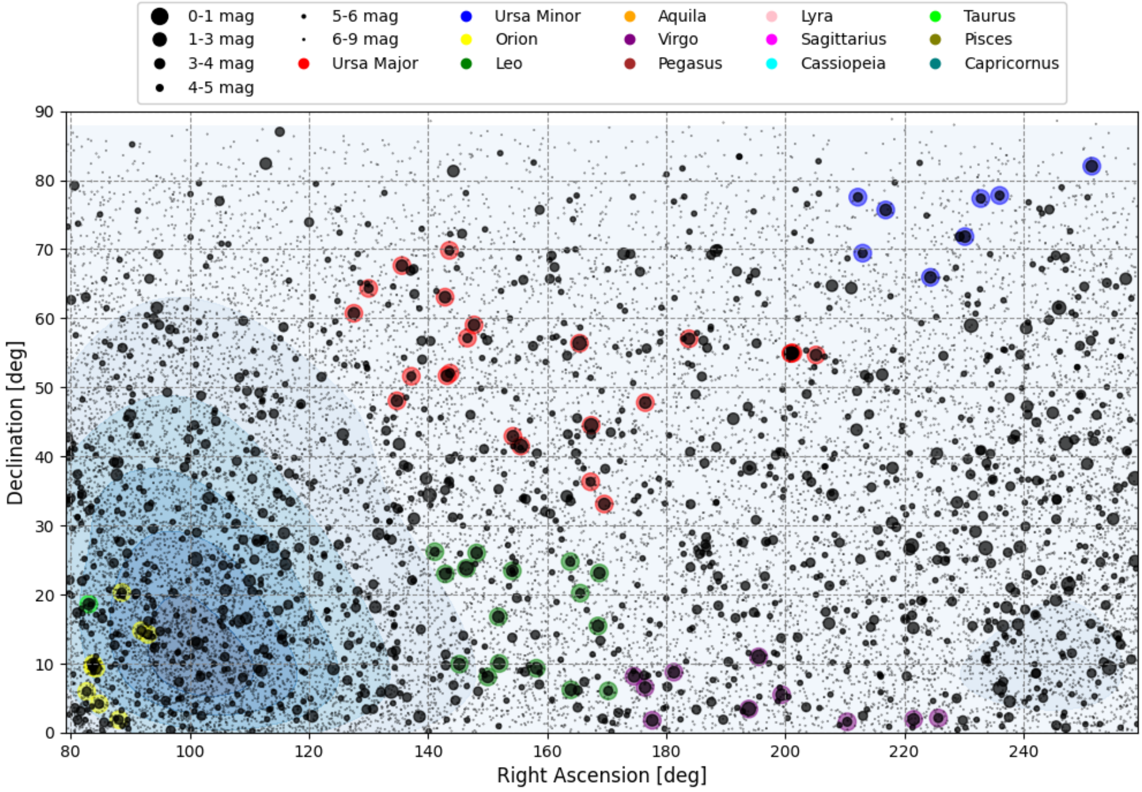

Figure 6: Starmap represented in declination and right ascension. The points and circles represent the stars in the sky and their sizes depends on their magnitude. The blue background density contour represents the more distant and faint stars. At more than 1kpc and with an 8.5 magnitude. The colors represent the different constellations that are on the list (stars brighter than 4.5 magnitude).

Therefore, our starmap of the current sky with the last changes is represented in Figure 7. This is now in the right ascension range of 130-310 degrees.

As discussed in subsection 2.3 our starmap is limited to a part of the sky, but over the entire declination range of the northern hemisphere. We will now limit ourselves to this right ascension range to do the time evolution, but it could be done for all stars in the northern hemisphere by simply changing the right ascension ranges. In addition, for the time evolution we have to take into account that we are currently at about 100000 years.

3.3 Starmap evolution

These three images: Figure 10, Figure 11 and Figure 8 (The first two figures are in Appendix A) represent the temporal evolution of the positions of the stars by proper motions from the present day to 100000 years from now. Because we have left the points of the constellations fixed, these displacements can be seen more clearly. Due to the large number of dots, if this were not fixed, between one image and the next, the displacements would not be clearly visible.

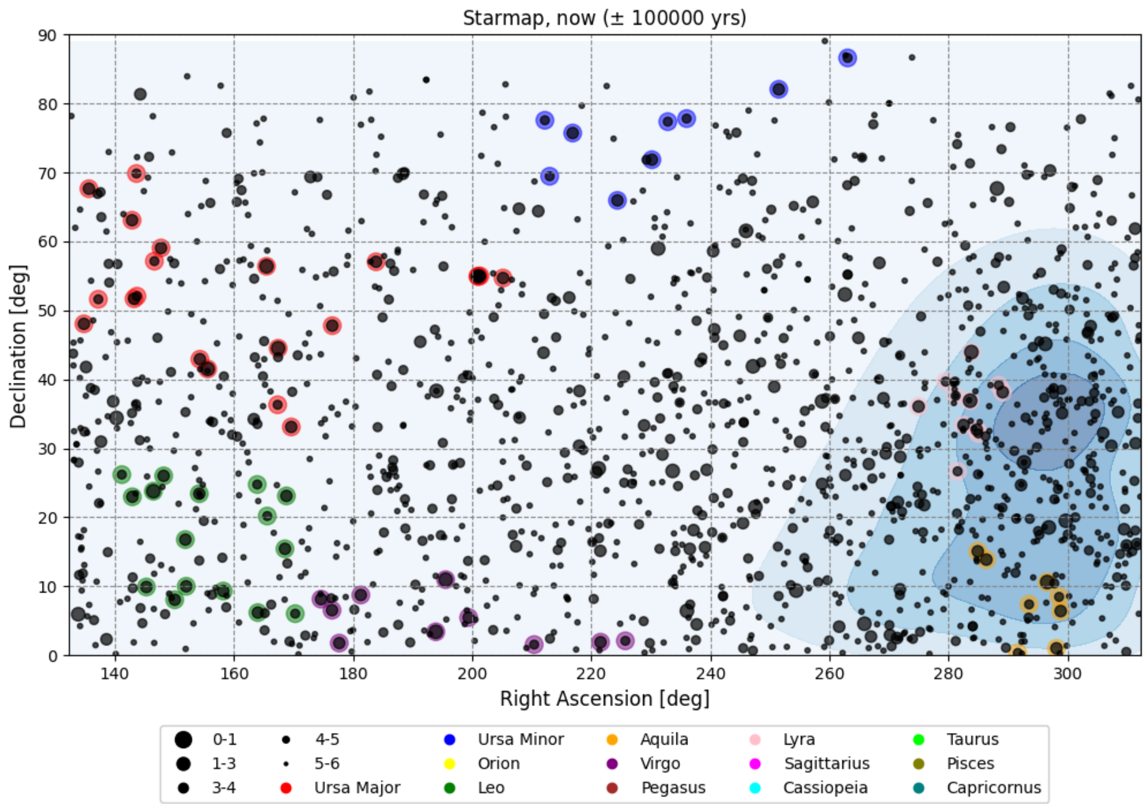

Figure 7: Current starmap represented in declination and right ascension. The points and circles represent the stars in the sky and their sizes depends on their magnitude (stars brighter than 6 magnitude). The blue background density contour represents the more distance and faint stars. The colors represent the different constellations that are on the list (stars brighter than 4.5 magnitude).

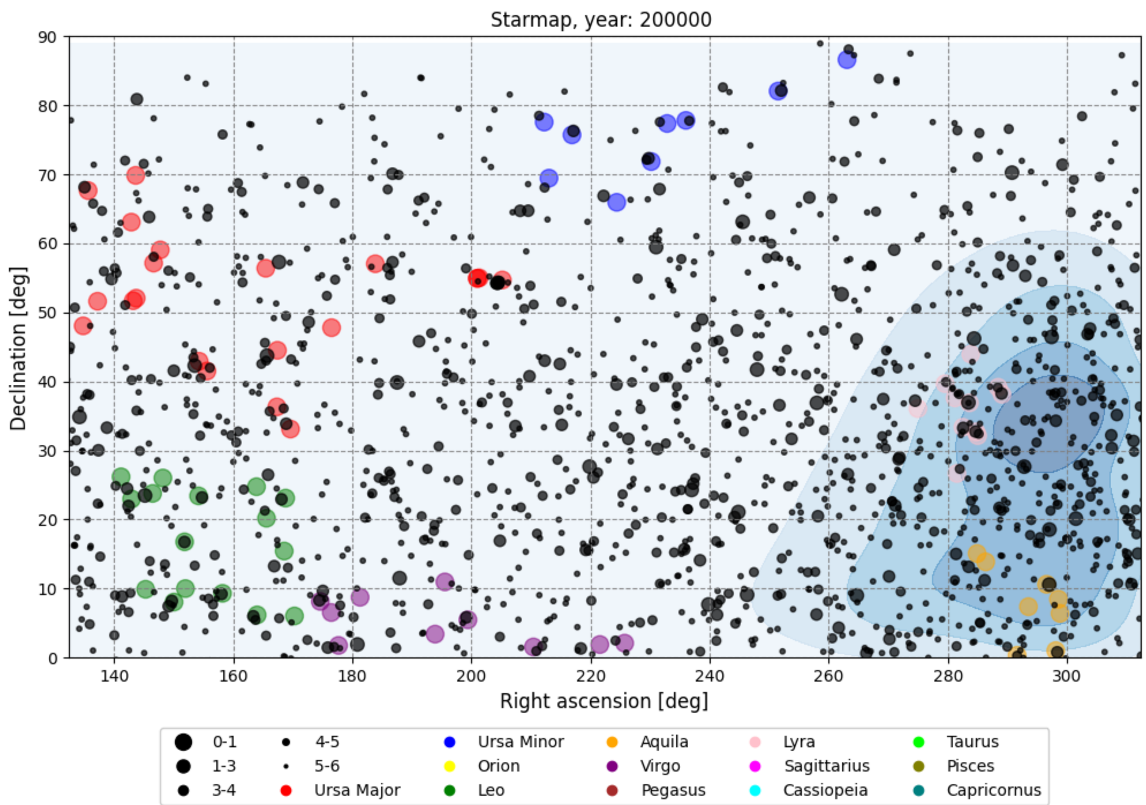

Figure 8: 200000yrs in the future starmap, represented in declination and right ascension.

This demonstrates what is already widely known, that the astronomical sky is not perfect and immutable in time, but like any part of nature they evolve and have their own dynamics. What is worth mentioning is the ease of predicting these movements thanks to databases as extensive as Gaia or Hipparcos, which allow this kind of predictions to be made with a low level of computation. In addition, it is also possible to do the reverse exercise and see what the astronomical sky was like 100000 years ago. This can be seen in the following three figures: Figure 12, Figure 13 and Figure 9 (The first two figures are in Appendix A).

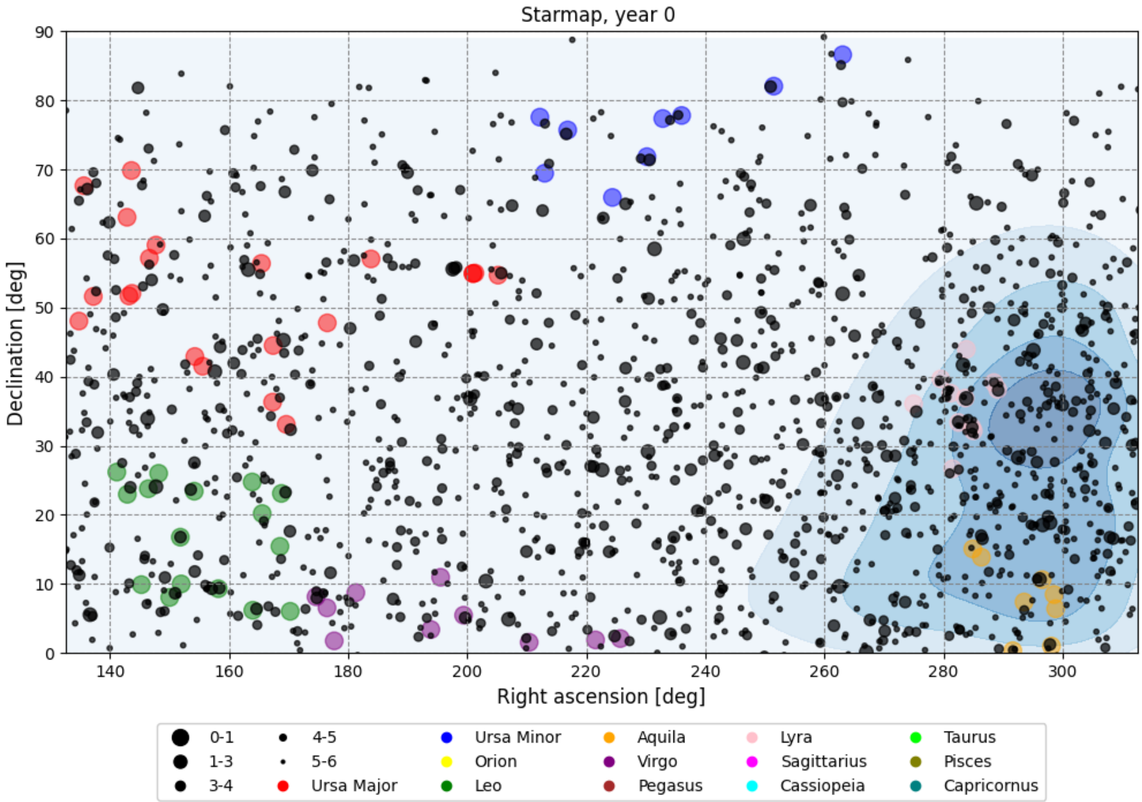

Figure 9: 100000yrs ago starmap, represented in declination and right ascension.

As it was previously mentioned, instead of limiting the range of right ascension, the code could be improved by making a transformation to horizontal coordinates and adding the stars currently visible at the specified location. Limiting only to the stars currently visible in the sky, since in our code we already use the sidereal time at the Teide observatory. There are already several codes that do this, like Berardi (2024) which offers several maps and ways to observe the sky in a very simple and complete way. However, if in future work we can improve our code by adding this, we could make a time evolution of which stars will be visible in the future at a specific location.

4 Conclusions

By following the methods described above (section 2), we have been able to reach a series of very clear results in this study:

Firstly, we have verified the enormous astrometric capabilities of the Gaia probe compared to the previous Hipparcos mission. In the apparent magnitude range of 8-10, Gaia is capable of offering us a sample with several orders of magnitude more than Hipparcos in the number of characterized stars and, as mentioned in the introduction, the constant improvements in the astrometric precision of Gaia greatly reduces measured errors for distance in the range below 1 *kpc*. It has also allowed us to characterize a greater number of faint stars and stars located at distances greater than 1 *kpc*. This highlights significant technological advances for the measurement instruments used on ESA's most recent mission.

On the other hand, we have been able to obtain maps of stellar densities for any range of right ascension and declination between 0 and 90 degrees. It has been possible to classify the stars in this map by magnitudes and we have also been able to distinguish constellations of stars in the generated maps.

Finally, we can highlight that we have been able to carry out a temporal study for our star map through the analysis of the proper motions. This has allowed us to estimate the shape of our sky in both past and future, spanning a total of 200,000 years. These results may be relevant, since although the changes observed in the star map in that range of years are not very significant, this relatively simple computational procedure could be useful in subsequent works to study how the components of the Milky Way evolve over time and to predict in detail how our galaxy is developing itself.

A Appendix: Starmaps

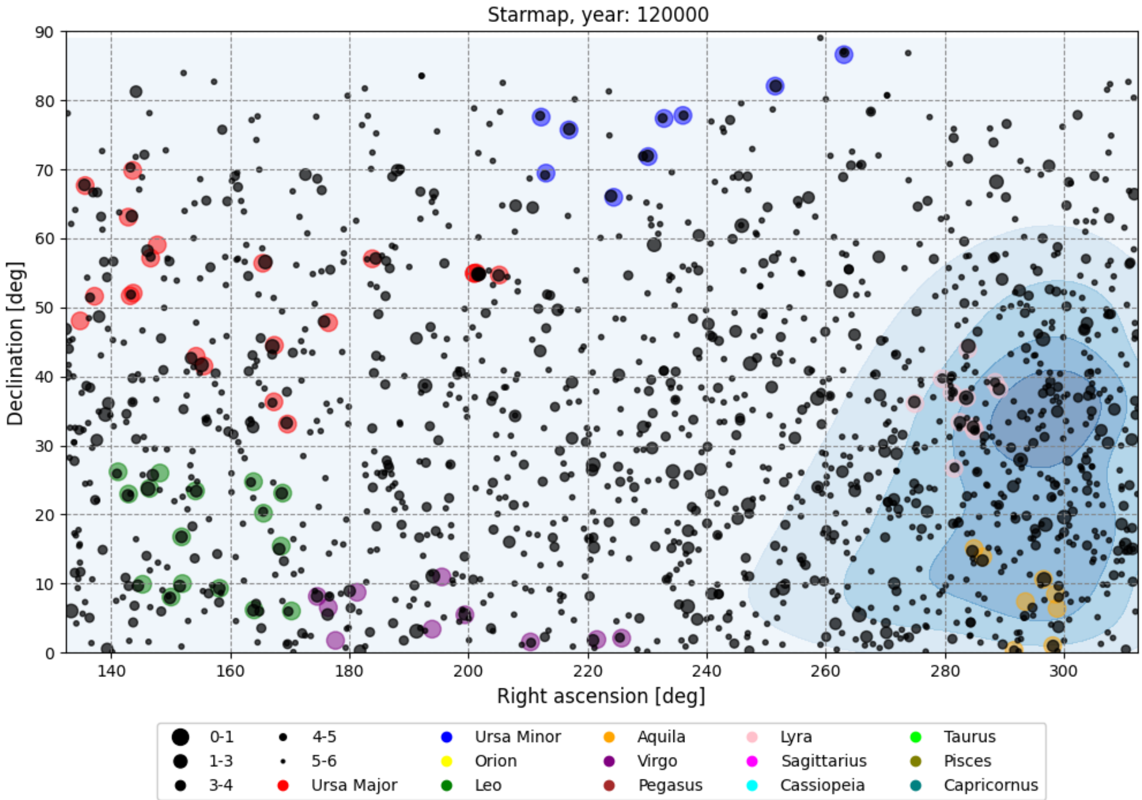

Figure 10: 20000 yrs in the future starmap, represented in declination and right ascension.

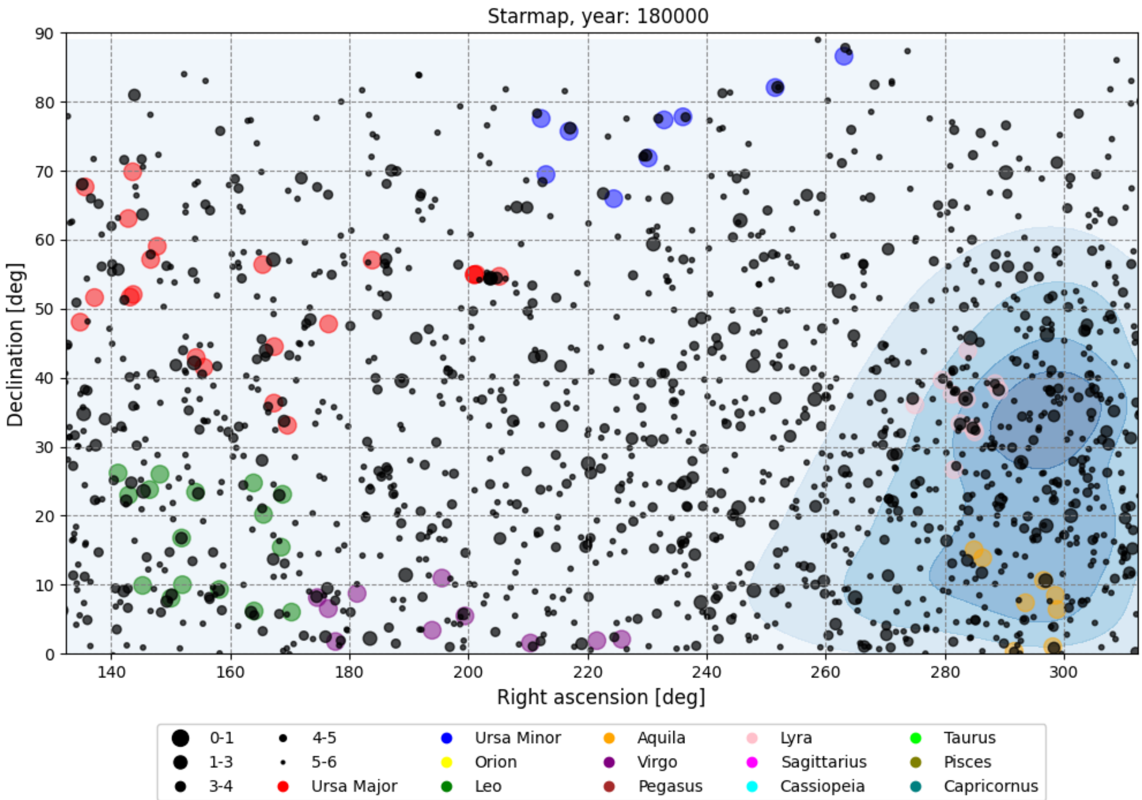

Figure 11: 80000 yrs in the future starmap, represented in declination and right ascension.

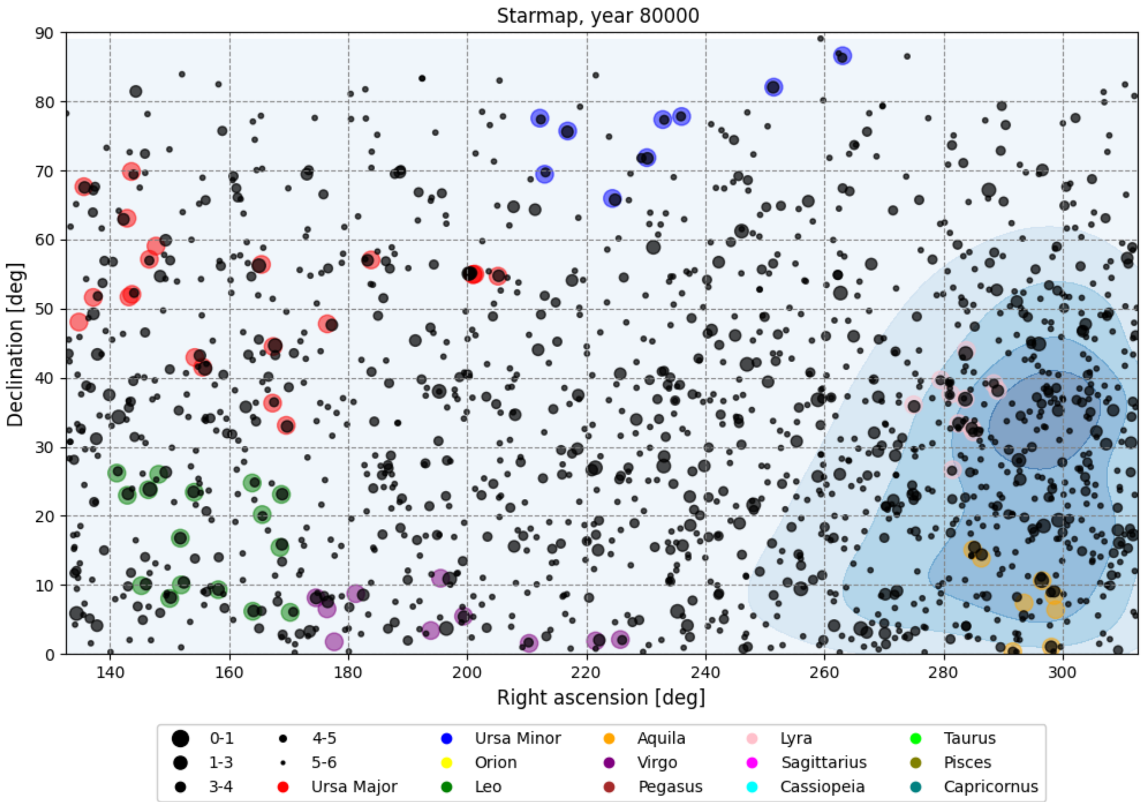

Figure 12: 20000 yrs ago starmap, represented in declination and right ascension.

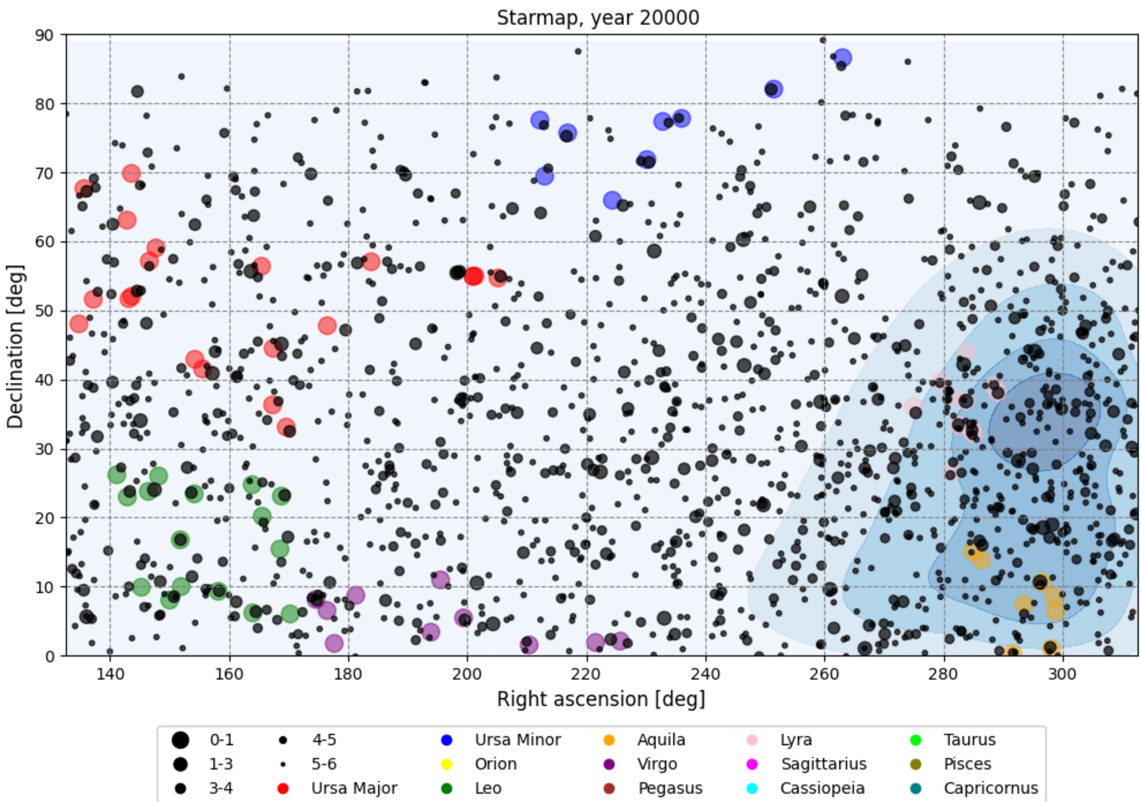

Figure 13: 80000 yrs ago starmap, represented in declination and right ascension.

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