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Tesi di Dottorato

Star formation rate
in the
solar neighborhood

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Summary

The project, described in this thesis, explores new methods to extract information through the use of color-magnitude diagrams (CMDs). In particular, the purpose of this thesis is to provide insight into the star formation rate in the solar neighborhood, analyzing the observations of the Hipparcos satellite.

An original technique of comparison has been devised:

- We employ the Bayesian Richardson-Lucy algorithm to the analysis of the observational errors in the CMDs by converting the CMD into an image (in effect, a CMD is an image, the intensity being the number of stars in a bin of effective temperature and luminosity, affected by a point spread function that originates from the error distributions of the parallaxes and photometry) and using a restoring point spread function derived from the known sources of error. The resulting reconstructions should be the best cleaned data set with which to perform analyses of the star formation rates;

- A synthetic population is built via Monte Carlo extractions of masses and ages, according the assumed initial mass function (IMF) and the star formation rate (SFR). Then, a suitable age-metallicity relation (AMR) gives the metallicity. The extracted synthetic stars are placed in the CMD by interpolations on the adopted stellar evolution tracks. In order to take into account the presence of binary stars, a chosen fraction of stars are assumed as binaries and coupled with a companion star. Once the number
of objects populating the artificial CMD equals that of the observed one, the procedure is stopped;

- To evaluate the goodness of the assumed model, we transform the theoretical and the observational CMDs in two dimensional histograms, choosing bin sizes in color and in absolute magnitude. Once the number of theoretical and observational objects is known in each bin, we implement a norma (a function of the residuals, as a \( \chi^2 \) or a Poissonian-\( \chi^2 \)) to quantify the differences between the two histograms. Then, one searches for the best set of parameters in the parameter space (through a simplex algorithm). Finally, the confidence limit of the results are evaluated through a bootstrap technique;

- In order to check the sensitivity of the recovered SFR to the different parametrical inputs (IMF, binaries, AMR), the algorithm is tested on artificial “Hipparcos” CMD;

- After fixing the less important parametrical inputs, the analysis is repeated on the real Hipparcos data, previously “cleaned” by the Richardson-Lucy algorithm.

Brief summary of chapters 1 - 6:
Chapter 1 gives an overview on the Galaxy and the solar neighborhood characteristics. Chapter 2 reviews the statistical basis that will be applied in the following chapters. Chapter 3 describes the observational data. In chapter 4 we apply the principles of stellar evolution to explain the Hipparcos CMD morphology. In chapter 5 we examine the qualitative and quantitative application of the Richardson-Lucy algorithm, in order to obtain an Hipparcos CMD cleaned from the observational errors. In chapter 6 we apply the method both to artificial CMDs, showing which parameters are critical for recovering the star formation rate, and to real Hipparcos data. In the last sections we test the recovered star formation against kinematic selection. Finally our results are compared with the ones of recent papers available in literature.
0.1 Conclusions and future work

The aim of this study was to develop a method for recovering as much information as possible from binned color-magnitude diagrams (CMDs). In particular, I applied the method to recover the local SFR from the Hipparcos color-magnitude diagram. Therefore, I developed a Galactic model for solar neighborhood: artificial stars are created by a random choice of mass and age from the assumed IMF and SFR(t), interpolating on a grid of evolutionary tracks, whose metallicity is determined by the adopted age-metallicity relation (AMR). A chosen fraction of these stars are selected as binaries and coupled with another star randomly chosen with the same procedure.

An artificial CMD is thus generated. The parameter space is searched for the combination of parameters giving the minimum distance, according a maximum likelihood statistic, between the theoretical and the observational CMDs.

In order to reduce the computational time, a set of partial CMDs was built, using them to produce whatever CMD: each partial CMD was generated with a step star formation, uniform in a given time interval and zero elsewhere. Thus, for each combination of IMF, binary distribution and AMR, the CMD corresponding to any SFR was computed as a linear combination of the partial CMDs.

In order to check the importance of the different parameters (IMF, binaries, AMR), I tested the algorithm on artificial “Hipparcos” CMD (fixing the minimum luminosity at $M_V \sim 3.5$, the completeness limit of the Hipparcos sample for stars within 80 pc). At these luminosities, the results indicate that the recovered SFR is weakly influenced by the right choice of IMF and binary fraction, but it is largely influenced by the adopted AMR. In particular, this result was checked assuming the observational AMR for the solar neighborhood by Nördstrom et al. (2004): in spite of the large dispersion of this relation, the simulation on the artificial CMD indicate that most of the information on the underlying SFR is still recovered. Finally, I applied the algorithm to real Hipparcos data. In contrast with artificial CMDs, the first problem was the pres-
ence of observational uncertainties (due to photometric and parallax errors). In order to take into account these uncertainties, I considered an innovative point of view: a CMD is an image, the intensity being the number of stars in a bin of effective temperature and luminosity, affected by a point spread function that originates from the error distributions of the parallax and of the photometry. Thus I treated the Hipparcos CMD with the same techniques that have been used for image restoration. In practice, I implemented the Richardson-Lucy algorithm to the analysis of color-magnitude diagrams affected by observational uncertainties: I converted the CMD into an image and, using a restoring point spread function derived from the observation, I “cleaned” the CMD (taking out the observational errors). I showed numerical experiments with artificial CMDs that demonstrate good recovery of the original image and establish convergence rates for ideal cases with single Gaussian uncertainties and Poisson noise using a $\chi^2$ statistic. Finally, this technique was applied to the Hipparcos sample of the solar neighborhood, recovering the best “cleaned” data set with which to perform analyses of the local star formation rate.

Assuming the observational AMR by Nördstrom et al. (2004), I tried to recover the SFR from this “cleaned” CMD. The resulting SFR indicates that the recent local history of the Galactic disk was very irregular (a bump around 2 Gyr is particularly evident). The mean value increases very steeply from 3-4 Gyr ago up to now, in a way qualitatively similar to the findings of Hernandez et al. (2000) and Bertelli & Nasi (2000). In particular, this result is is quite independent against kinematic selections, suggesting that:

1. The local contamination of halo and thick disk stars is negligible and/or these populations are older than 6 Gyr (the possibility to infer the older SFR is hindered by the completeness limit in absolute magnitude);

2. In the last 5-6 Gyr, all the stellar generations are well sampled; in other words, the recovered local SFR is not biased by dynamical diffusion and the local volume is not “depleted” by old disk stars. Moreover, the recovered column-integrated SFR by Vergely et al. (2002) is very similar to
our local SFR, suggesting that the dynamical diffusion wasn’t so efficient in the last 5-6 Gyr.

The timescale of the recovered SFR seems too long (larger than the dynamical timescale) to be attributed to local events: an accretion of a satellite galaxy is suspected.

This work allowed to develop a general method to extract informations (in our case the local SFR) from a color-magnitude diagram. The observational CMD is “cleaned” with a Richardson-Lucy algorithm, then the chosen information (SFR) is recovered. In this last process, all the parameters with a not critical influence are fixed to a given value. However, if the IMF and the binary fraction are not critical inputs to recover the SFR from Hipparcos stars brighter than $M_V \sim 3.5$, this condition falls when deeper data are adopted. In this situation (for example if future possible data from the Gaia mission will be available), new numerical experiments would be necessary in order to explore the sensitivity of the result to the adopted parameters. The method can be easily applied to the analysis of the SFR of the CMD of dwarf galaxies, for which the distance among the stars is negligible with respect to distance of the Galaxy from us.

Another natural extension of this method could involves the analyses of not-local Galactic fields: adopting spatial distribution for the different Galactic components, it would be possible to study the disk SFR on larger scale lengths. The typical data for a similar analyses would be the color-apparent magnitude diagram for field observations (stars along the line of sight, with unknown distance, chemical composition, mass and age). In contrast with local stars, whose the uncertainties affecting the CMD are mainly due to parallax errors, for field stars the uncertainties are mainly photometric: the modified version of the Richardson-Lucy algorithm should adopt a point spread function, whose the width varies as function of the magnitude (increasing towards faint magnitudes where the photometric error is larger). For Galactic field stars the open questions and thus the possible future research are manifold. For example,
comparing the results for local and field stellar samples could give useful informations. The local sample is the ideal place to study the disk stars, but it is less informative about thick disk stars. In contrast, field stars are very informative on the thick disk. The combination of the two data could give information on the Galaxy as a whole. The local and the field disk stars could show differences in the AMR, SFR and IMF. In particular, the possibility that a time dependent IMF is necessary to explain the data could clear if this function is a real universal quantity.

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