Cloud Computing Bayesian Approach to Study Effects of Binary Stars on Ages of Star Clusters

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Abstract. We apply bayesian algorithms to studying the effects of binary stellar population models on the age determination of 46 new star clusters in Gaia DR2. The ages of star clusters are obtained via color-magnitude diagram (CMDs). The data are selected from two works. Our analysis focus on exploring the potential of bayesian algorithm to estimate the effects of binary stars on the parameter determination of star clusters. Our work is based on simple stellar population models of binary stars and single stars. As a result, the bayesian analysis shows that binary stars have significant effects on the determination of ages of star clusters. The models with binary stars report older ages for most star clusters. The age difference between binary-star models and single-star models follows a Gaussian distribution with mean of 1.2 Gyr.

Keywords: Cloud computing; Bayesian; Age; Star clusters.

1. Introduction
The determination of ages of star clusters is crucial for understanding the formation history of galaxies. The age of stellar population can be estimated from different methods, e.g., the morphology of the color-magnitude diagram (CMD) (Catelan 2018; Soderblom 2010; Vandenberg et al. 1996)[1-3] and spectral energy distributions. Recently, Valcin et al. (2020)[4] made use of bayesian approach to estimate the parameters of old globular clusters from full CMD fitting, and then infer the age of the universe. However, a kind of important stars, binary stars were not taken into account. In fact, binary stars play significant roles in understanding stellar population synthesis works and for testing stellar evolution theory (Wang et al. 2020)[5]. They affect CMDs of star clusters obviously. The binary fraction in star clusters can therefore be determined from CMD. For example, Belloni et al. (2017)[6] derived the binary fraction and their mass ratio distribution via CMDs. Moreover, binary stars play an important role in understanding special stars such as blue stragglers, yellow stragglers and red stragglers (Li et al. 2014)[7]. They are also sensitive to the structures of CMD such as the broad main sequences, the extended main sequence turn-offs (Li & Deng 2018; Luo & Li 2018)[8-9] and red giant clumps (Li et al. 2020)[10]. Therefore, it is important to take binary stars into account in building synthetic CMDs of stellar populations.
At present, astrophysical parameters of stellar populations of star clusters are mainly obtained by CMD fitting, including age. However, different ages may be reported by synthetic simple stellar population models that involve binary stars or not, and the effect of the inclusion of binary stars in stellar population models is not clear. In order to check the effects of binary stars on the age determination of star clusters, this work adopts the bayesian technique which serves as a promising research method. In fact, bayesian method is used wider and wider in astrophysical studies. For example, Smith et al. (2021)[11] concluded that the bayesian inference is computationally tractable for...
gravitational waves from binary neutron star mergers in 3G observatories. Many papers take bayesian techniques to study cosmological parameter inference (e.g., Jasche et al. 2010; Li et al. 2013; Sahlholdt et al. 2019; Mandal et al. 2021)[12-15]. Therefore, it is possible to use bayesian techniques to study the effects of binary stars on the age decision of star clusters. This work aims to have a try and the innovation of this paper lies in the application of the method to estimate effects of binary stars on ages of star clusters.

The structure of this paper is as follows. In section 2 we give an introduction to the data used in the study and the general idea of bayesian algorithm. Our results are given in Section 3. The conclusion and discussion are finally given in Section 4.

2. Data and Methodology
We use the catalog of 49 new open clusters in Gaia DR2. The data of simulation parameters are derived from the works of Li et al. (2021)[16] and Liu & Pang (2019)[17]. Four star clusters were removed because their ages are too small (near zero) to be studied. The leaving 46 clusters are chosen for our work. The fundamental parameters of 46 clusters such as age, distance modulus, metallicity, extinction and binary fraction are available.

In order to find out the impact of binary stars on the age determination of star clusters, we compare the ages derived from Li et al. (2021) [16] with those from Liu & Pang (2019)[17]. Two sets of ages of 46 clusters are obtained via the same observed CMDs but different stellar population models. One comes from simple stellar population models of binary stars (bsSSP), and the other comes from simple stellar population models of single stars (ssSSP). The bsSSP models are built by a CMD fitting software Powerful CMD (Li et al. 2017)[18] designed based on the advanced stellar population synthesis model (ASPS) (Li et al. 2016)[19]. The ssSSP models are obtained from the Padova database of stellar evolutionary tracks (Liu & Pang 2019; Marigo et al. 2017)[17, 20]. The Powerful CMD and Padova are the simulation tools in this work. We take ages of 46 clusters as our sample parameters and attempt to use bayesian techniques (Li, Yan-Rong and Wang et al. 2013)[21] to investigate the correlation between the ages derived from bsSSP and ssSSP models. Appropriate descriptions and formula for techniques and evaluations are similar to the reference in this work and the environment of the algorithms is implemented based on Python.

3. Results
The study is based on two histograms of ages from bsSSP and ssSSP models. Then density functions are calculated using Gaussian kernel density estimation (KDEs). One can see figures 1 and 2 for the details. The ages of every star cluster, which are determined using two kinds of stellar population models are directly compared in figure 3. In the bayesian study, we take the age distributions from ssSSP models and bsSSP models as the prior and posterior distribution respectively, and then the probability distribution function (PDF) of likelihood function (see Figure 4) is calculated. It is unnecessary to calculate the specific value of the likelihood function, because the influence of binary stars can be judged from the changing trends of likelihood function with the parameters.
We apply the bayesian technique to compare the distributions of ages of star clusters that are derived respectively from bsSSP models and ssSSP models. The result shows that the effects of binary stars on the age determination of clusters are fairly obvious. This is confirmed by both the likelihood function and KDE.

Figure 1. Histograms of ages derived from bsSSP and ssSSP models.

Figure 2. KDEs of ages derived from bsSSP and ssSSP models.
Figure 3. Comparison of ages determined by CMD fitting from different models.

Figure 4. Similar to figure 2, but for the likelihood function.

4. Conclusion
The bayesian method is applied to the data of 46 new open clusters, whose ages are determined from ssSSP and bsSSP models. The effect of the inclusion of binary stars in stellar population models on the age determination of star clusters is well studied in this literature. Binary stars are shown to have some significant effects, and they should be considered in future works of the age determination of star clusters and galaxies. We summarize and discuss on this work as follows.

- It is important to taken into account binary stars when building stellar populations and computing the synthetic CMDs of populations. This will help to get more accurate ages of star clusters, and star formation histories of stellar populations. The result of bayesian analysis indicates that the ages of the star clusters determined from bsSSP models are likely to be increased by about 25% compared with those from ssSSP models.
- Bayesian approach enables a direct probe of the effects of different factors involved in parameter determination. However, there are still disadvantages in using this approach, which should be investigated deeply. One of the disadvantages is over-fitting. In addition, it is
sensitive to the expression of input data and the prediction effect is not enough good when the parameter attributes are correlated.

- Our samples are not large enough and not complete. This can affect the statistical results. In addition, there are some uncertainties in stellar population models, which relate to the uncertainties of stellar evolutionary models and stellar library. They are out of this study but should be discussed in the future.

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