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# TWO TOOLS FOR ESTIMATING STAR CLUSTER PARAMETERS

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**ABSTRACT.** A star cluster is a composition of stars held together by the overall gravitational field of the whole cluster. The stars of a given cluster are born in a giant molecular cloud and, as such, can be regarded as objects with almost equal ages. Furthermore, assuming that the initial material in the cloud is perfectly mixed, we may also say that the metallicity of all cluster members is the same. Four parameters (distance, extinction or reddening, age, and metallicity) are standardly used to describe star clusters. Their knowledge is essential for studying galaxies' local and global properties (especially our own Galaxy). However, deriving these parameters may take time and effort. Thanks to the Gaia mission's parallax measurements, we can determine the distances of stars (and clusters) within our Galaxy with unprecedented precision. Therefore, we can remove the distance from the list of free parameters. We developed two different tools for estimating cluster parameters: 1) Metalcode, an automatic tool focused on deriving metallicities of open clusters, and 2) Stellar Isochrone Fitting Tool (StIFT), a tool for fitting a grid of isochrones for any photometric system available. We present both tools in more detail.

**Keywords:** Galaxy: abundances; Hertzsprung-Russell and C-M diagrams; open clusters and associations: general; stars: abundances.

**АНОТАЦІЯ.** Завдяки останнім даним GAIA тепер можливо більш детально вивчати найближчі відкриті скупчення. Внутрішня структура та кінематичні характеристики відомі лише для кількох скупчень, таких як Гіади та Плеяди. Однак ці характеристики є важливими як вхідні параметри для моделі, що стосуються формування та еволюції зоряних скупчень. Нещодавні публікації представили однорідний вибір із майже 8 000 галактичних зоряних скупчень (Hunt & Reffert, 2023). Однак оцінка

параметрів зоряного скупчення все ще триває. Зоряне скупчення – це композиція зірок, які утримуються разом загальним полем тяжіння всього скупчення. Зорі даного скупчення народжуються у гігантській молекулярній хмарі і можуть розглядатися як об'єкти майже однакового віку. Крім того, припускаючи, що початковий матеріал у хмарі ідеально змішаний, ми також можемо сказати, що металічність усіх членів скупчення однакова. Для опису зоряних скупчень стандартно використовуються чотири параметри (відстань, поглинання або почервоніння, вік і металічність). Їх знання необхідні для вивчення локальних і глобальних властивостей галактик (особливо нашої власної Галактики). Однак визначення цих параметрів може зайняти час і зусилля. Завдяки вимірюванням паралакса, проведеним місією Gaia, ми можемо визначити відстані до зір (і скупчень) у нашій Галактиці з безпрецедентною точністю. Тому ми можемо прибрати відстань зі списку вільних параметрів. Ми розробили два різних інструменти для оцінки параметрів кластерів: 1) Metalcode, автоматичний інструмент, зосереджений на отриманні металічності розсіяних скупчень, і 2) Інструмент підгонки ізохрон зір. (StIFT), інструмент для підгонки сітки ізохрон для будь-якої доступної фотометричної системи.

**Ключові слова:** Галактика: хімічний склад; діаграми Герцшпрунга-Рассела та C-M; розсіяні скупчення та асоціації; зорі: хімічний склад.

## 1. Introduction

Star clusters are the most essential astrophysical laboratories for the formation and evolution of individual stars (members) and the Milky Way as a global galaxy. They are physically related groups of stars held together by mutual gravitational attraction. Therefore,

these populate a limited region of space, typically much smaller than their distance from the Sun, so the members are all approximately at the same distance. They are believed to originate from sizeable cosmic gas and dust clouds (diffuse nebulae) in the Milky Way and to continue to orbit the Milky Way through the disk. In many clouds visible as bright diffuse nebulae, star formation still occurs so we can observe the birth of new young star clusters. This process of formation takes only a short time (a few Myrs) compared to the lifetime of the cluster, so, speaking in terms of stellar evolution, all member stars are of similar age. Also, as all the stars in a cluster are formed from the same diffuse nebula, they are all of a similar initial chemical composition. Hence, star clusters are of great interest to scientists:

- The cluster members are all about the same distance from the Sun.
- They have within a few million years approximately the same age.
- The chemical composition of the members is relatively homogeneous within a cluster, but the metallicities of the various open clusters range from about -1.5 to +0.6 dex compared to the Sun.
- The member stars have different masses, ranging from about  $120 M_{\odot}$  for the most massive stars in very young clusters to less than  $0.08 M_{\odot}$ .

The age and metallicity are, in general, not straightforward to determine for Galactic field stars. Star clusters, on the other hand, represent samples of objects of constant age and homogeneous chemical composition, suited for the study of processes linked to stellar structure and evolution and to fix lines or loci in several of the most important astrophysical diagrams, such as the colour-magnitude diagram (CMD) or Hertzsprung-Russell diagram (HRD). So, any astrophysical phenomenon can be studied for members of star clusters in correlation with age, distance, and metallicity.

A star cluster is a composition of stars held together by the overall gravitational field of the whole cluster. The stars of a given cluster are born in a giant molecular cloud, and as such can be regarded as objects with almost equal ages. Furthermore, assuming that the initial material in the cloud is perfectly mixed, we may also say that the metallicity of all cluster members is the same.

However, deriving the four parameters may not always be simple. One can always use the isochrone fitting technique to determine the distance, the extinction and the age of a cluster. Furthermore, thanks to the parallax measurements from the Gaia mission (Cantat-Gaudin, 2022), we can determine the distances of stars (and clusters) within our Galaxy with unprecedented

precision. Therefore, we can remove the distance from the list of the free parameters.

Dealing with the metallicity is not as simple. While isochrone fitting in the CMD can provide fairly precise results (Dias et al., 2021), it is not very sensitive to variations in metallicity and solar metallicity is often assumed. Another approach is to measure the stellar members' spectra and determine their abundances (Heiter et al., 2014). However, this approach can be limited by the distances of the target stars and, therefore, is not suited for the distant clusters.

Here, we present two newly developed tools which significantly improve the situation of fitting cluster parameters and astrophysical parameters of stars. They can be universal used including user-defined isochrone grids, for example

## 2. The two tools

In the following, we present the two tools in more detail. They have already been successfully applied to star clusters (Paunzen et al., 2021) and individual star groups (Faltová et al., 2021).

### 2.1. Metalcode

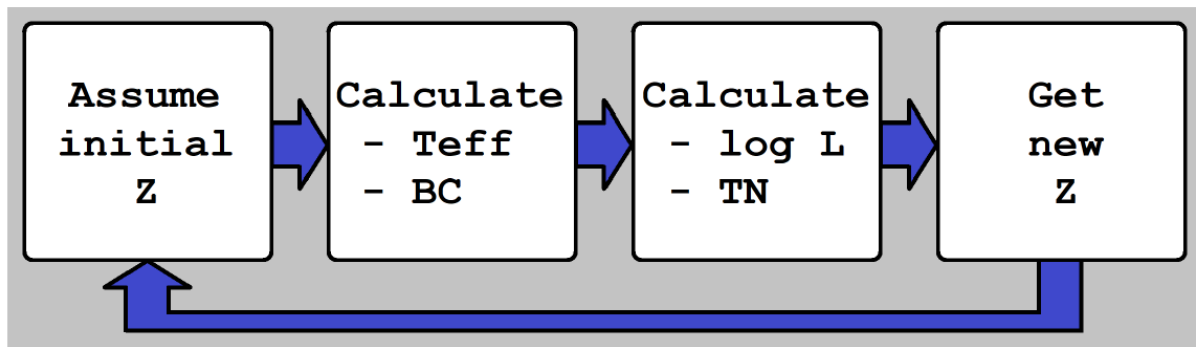
Metalcode<sup>1</sup> is a new, fully automatic procedure capable of computing the four main cluster parameters (distance, reddening, age, and metallicity). The approach is based on the work by Pöhl & Paunzen (2010) and focuses primarily on determining metallicities of star clusters. The method for determining metallicities, presented in Pöhl & Paunzen (2010), is based on an iterative approach. It requires a list of stars for which a photometric brightness and a photometric colour are included. In principle, any photometric system can be used while the isochrones are available. Furthermore, an initial estimate of the cluster's distance and the reddening is needed before the method can be used. It is possible to vary the values of these two cluster parameters during the iterations.

Another important part of the method is the isochrone grid which consists of the  $(\log L, \log T_{\text{eff}})$  curves for a given set of age and metallicity values. Before the iterative process is started, the effective temperatures in this grid need to be normalised with respect to the zero-age-main-sequence (ZAMS) – this step is described below.

Overall, the iterative process (Fig. 1) can be summarised in four steps:

1. Assume the initial value of metallicity. In the first iteration, this can be taken to be the solar metallicity value. Any solar metallicity value can be

<sup>1</sup><https://github.com/mpiecka/metalcode>



$$T_N = \log T_{\text{eff}} - \log T_{\text{eff}, \text{ZAMS}} | Z_{\odot}$$

Figure 1: The working flow of metalcode (Sect. 2.1.)

used, but it must be applied consistently during the process.

2. For each of the cluster members, calculate the effective temperature  $T_{\text{eff}}$  and the bolometric correction  $BC$ . Both calibrations are generally based on polynomial relations with the photometric colour and metallicity. Pöhl & Paunzen (2010) applied the calibrations from Alonso et al. (1996) and Flower (1996). These calibrations require the transformation between  $Z$  and  $[\text{Fe}/\text{H}]$ .
3. Calculate the luminosity  $\log L$  and the normalised logarithmic effective temperature  $T_N$  for each of the members. The normalisation is performed by subtracting  $\log T_{\text{eff}}$  from the value on the solar-metallicity ZAMS:  $T_N = \log T_{\text{eff}} - \log T_{\text{eff}, \text{ZAMS}} | Z_{\odot}$ .
4. Compare the distribution of the data points in the  $(\log L, T_N)$ , or shortly LTN (we will use this abbreviation from now on), diagram with the prepared isochrone grid. Pick the isochrone which best fits the observed data distribution. This gives a new estimate of the metallicity (and of the age).

At the end, the final metallicity value is compared with the initial estimate. The iterations are terminated once the values are the same (or differ by a certain threshold value at most).

This method has been applied several times and proven fairly robust (see Netopil et al., 2016). It was mainly used for stars on the main sequence. The provided results are in good agreement with the spectroscopic observations.

The utilisation of the normalised temperature makes the LTN diagram much more viable for determining metallicities than a CMD or a classical temperature-luminosity diagram. The reason for this is the in-

creased sensitivity to the metallicity change, as already demonstrated in Pöhl & Paunzen (2010).

Metalcode is a procedure that could apply this method automatically. To do so, it is important first to analyse possible issues. For example, several factors can influence the precision of determining metallicity from the LTN diagram:

- A binary sequence creates an additional distribution of stars, shifting towards negative  $T_N$  values. This does not affect the results much when the isochrone fitting is performed manually since a skilled researcher can easily distinguish between the two sequences. However, it could influence an automatic procedure.
- Differential extinction can appreciably broaden the width of the MS in the CMD. This broadens the distribution along the horizontal main-sequence "line" in the LTN diagram, which can result in a higher error in the metallicity determination.
- Imperfections in the effective temperature calibrations can cause luminosity-dependent systematic offsets. The effect is further increased when combined with the differential extinction.

For testing purposes, we have written a short code which creates a data set of stars for a synthetic cluster based on the isochrone grid. This code is used to test the above-mentioned sub-procedures, allows us to introduce a binary sequence, and gives us control of the width of the main sequence. Therefore, the influence of various effects can be analysed.

The code is presently equipped with a basic isochrone fitting procedure. Its performance was tested for Johnson  $BV$ , 2MASS  $JK_s$ , and Gaia  $GBpRp$  photometric systems.

## 2.2. Stellar Isochrone Fitting Tool (StIFT)

Stellar Isochrone Fitting Tool (StIFT<sup>2</sup>) is a multi-platform stand-alone tool that estimates the age, radius, mass, and evolutionary phase of a star defined by its  $T_{\text{eff}}$  and  $\log L$ . The computation is done by interpolating isochrones from the default grid or custom data set. The tool reacts to the demand for missing features of currently available tools; it offers easier manipulation and provides all necessary options to simplify the work of astrophysicists.

The evolutionary tracks are defined as a parameters grid for different metallicities and ages. StIFT is a tool for interpolating within a user-defined grid of isochrones, for example. Estimating missing characteristics is described in Malkov et al. (2009) and Sichevskij (2017). Firstly, the nearest isochrones are found for a star  $(x, y)$  defined by effective temperature and luminosity. Here, four stars are selected as the nearest neighbours of the input star (as shown in Fig. 2).

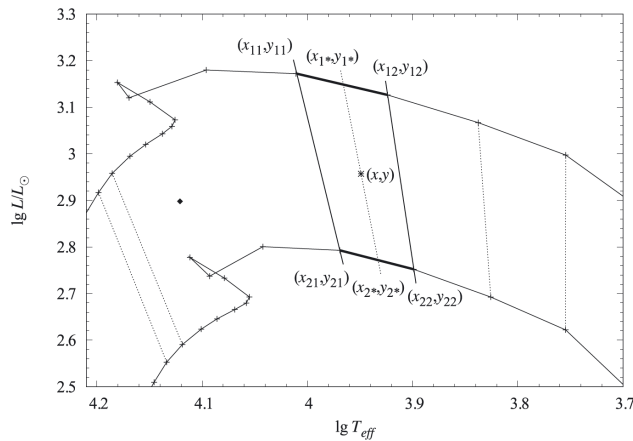


Figure 2: Nearest isochrones (upper and lower tracks) are used for estimating missing parameters, four neighbours create a figure, and a line connects the isochrones with the input star. Credit: Malkov et al. (2009).

Secondly, a line  $[(x_{1*}, y_{1*}), (x_{2*}, y_{2*})]$  is found within this area that connects the isochrones and the input star. The  $x_{2*}$  coordinate comes as a root of quadratic equation solving the position of line points. Other line points' coordinates are obtained by linear interpolation, for example, the  $y_{1*}$  from the following formula:

$$y_{1*} = y_{12} + \frac{y_{12} - y_{11}}{x_{22} - x_{21}}(x_{2*} - x_{22}).$$

The line points are interpolated for the  $y$  coordinate and all missing stellar parameters. They are then used in the next step, which requires performing interpolation to get the results for the input point. For example,

mass ( $\mu$ ) would be obtained from line points' masses ( $\mu_{1*}$  and  $\mu_{2*}$ ) by the following formula:

$$\mu = \mu_{1*} + \frac{\mu_{2*} - \mu_{1*}}{x_{2*} - x_{1*}}(x - x_{1*}).$$

This kind of uncertainty creates a standard deviation ( $\sigma$ ), which can be calculated as a square root of a sum of squared differences between the mean value ( $\mu$ ) and other values ( $x$ ) divided by the number of used points ( $N$ ):

$$\sigma = \sqrt{\frac{\sum(x - \mu)^2}{N}}.$$

Besides estimating the mean value, the StIFT also works with uncertainties. That is, during the process of estimating the result, an error can occur. This comes from using linear interpolation and can be calculated by partial derivation. Another kind of uncertainty comes from using input parameters which are not precise. Other than linear attributes, they must be converted to linear ones to get the correct value. For example, age must be converted from decimal exponent format to years before calculating the deviation and transformed back after. Further, I refer to uncertainty as the combination of interpolation error and standard deviation. The uncertainty for each parameter is obtained from the following formula:

$$\text{uncertainty} = \sqrt{\text{error}^2 + \text{deviation}^2}.$$

In Fig. 3, the GUI version of StIFT is shown. Currently, the tool includes the following features:

- Supported input: filling the form, clicking graph or uploading input file
- Showing results in the result table
- Uploading custom grid data or using default grid data
- Graph representation of grid data
- Exporting result data
- Filtering results based on the evolutionary phase
- Filtering tracks based on the evolutionary phase
- Uncertainty estimation
- Text mode, fast mode

Running the application requires Java 11.

## 3. Conclusions and Outlook

With the most recent Gaia data releases, studying nearby open clusters in more detail is now possible. The internal structure and kinematic characteristics are only known for a few clusters like the

<sup>2</sup><https://github.com/Johaney-s/StIFT>

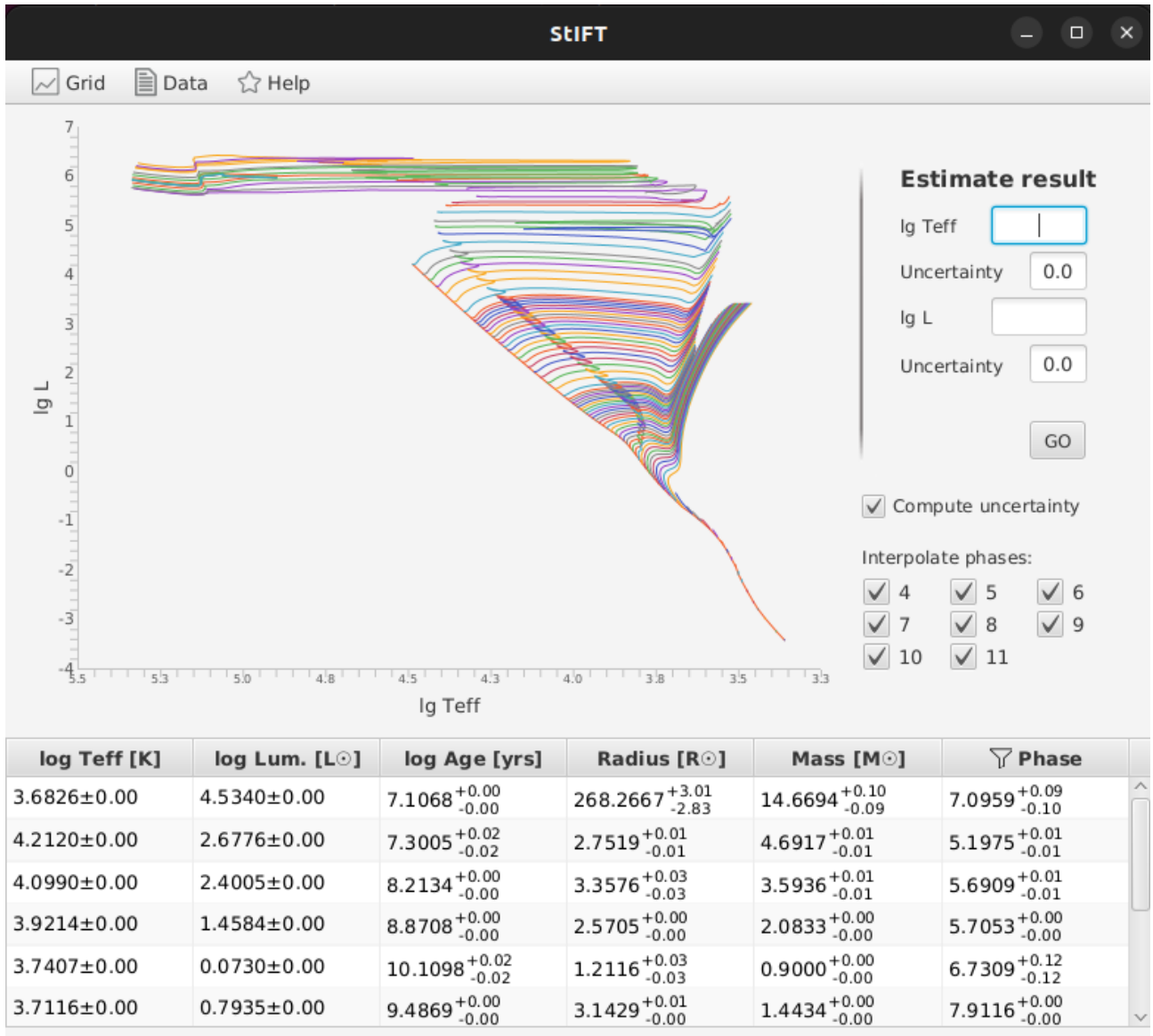


Figure 3: A snapshot of the GUI version of StIFT (Sect. 2.2.)

Hyades and Pleiades. However, these characteristics are essential as input parameters for models dealing with the formation and evolution of star clusters (Piecka & Paunzen, 2021).

Recent publications presented a homogeneous selection of almost 8 000 Galactic star clusters (Hunt & Reffert, 2023). However, the estimation of star cluster parameters is still not straightforward and is limited by several observational and theoretical uncertainties. No The homogeneous method allows the age and metallicity estimate for a given distance, and reddening is available.

In this paper, we present two new tools which help to find a solution for this problem. They are user-friendly and can be extended to any new photometric and isochrone set.

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