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ysoisochrone: A Python package to estimate masses and ages for YSOs

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Statement of Need

At this moment, there are a few existing tools and packages that can be used to handle stellar evolutionary tracks and to estimate stellar mass and age for pre-main sequence stars. For example, `isochrones` (Morton, 2015) provides a Python interface to access the MIST grids (Choi et al., 2016; Dotter, 2016), and the PARSEC team provides a web interface to access different versions of their tracks together with some useful web-based tools. More recently, Squicciarini & Bonavita (2022) developed and published another Python package `MADYS`, which can be used to derive ages and masses for pre-main sequence stars from multi-wavelengths photometric data with the extinction corrected according to extinction maps and laws. This code could also utilize different stellar evolutionary models. `MADYS` provides easy access to obtaining photometric age and mass estimates for large groups of young stellar or substellar objects.

Here we introduce `ysoisochrone`, a Python package that utilizes stellar evolutionary tracks to estimate stellar masses and ages of pre-main sequence stars with a Bayesian framework. While several papers in the literature utilize this method (e.g., Fernandes et al., 2023; Jørgensen & Lindegren, 2005; Pascucci et al., 2016), an open-source tool implementing this method is not available. `ysoisochrone` fills this gap and provides a uniform platform to handle different evolutionary models with easy access to Bayesian framework along with tutorials and detailed documentation for first users.

Background and Methods

There has been a long history of estimating stellar ages and masses from stellar evolutionary models (e.g., Baraffe et al., 2015; Feiden, 2016; Siess et al., 2000). Different methods have been employed, from finding the closest track to an object's luminosity and temperature (e.g., Manara et al., 2023) to employing a Bayesian approach which enables estimating uncertainties on the inferred ages and masses (e.g., Andrews et al., 2013; Gennaro et al., 2012; Jørgensen & Lindegren, 2005). Our primary method is a Bayesian inference approach, and the Python code builds on the IDL version developed by Pascucci et al. (2016). The code estimates the stellar mass, age, and associated uncertainties by comparing a star's effective temperature (T_{eff}), bolometric luminosity (L_{bol}), and their uncertainties with different stellar evolutionary models, including those specifically developed for young stellar objects (YSOs). The conditional likelihood function assumes log-uniform priors and can be written as:

$$
\begin{aligned}
\mathcal{L}(\log T_i, \log L_i \mid \log T_{\rm obs}, \log L_{\rm obs}) &= \frac{1}{2\pi\sigma_{\log T_{\rm obs}}\sigma_{\log L_{\rm obs}}} \\
&\times \exp\left(-\frac{1}{2}\left[\frac{(\log T_{\rm obs}-\log T_i)^2}{\sigma^2_{\log T_{\rm obs}}} + \frac{(\log L_{\rm obs}-\log L_i)^2}{\sigma^2_{\log L_{\rm obs}}}\right]\right),
\end{aligned} \tag{1}
$$

where the T and L are the effective temperature and bolometric luminosity, respectively. T_i, L_i are the values from the evolutionary model grids, and $T_{\rm obs}, L_{\rm obs}$ are the observed values for each target with their uncertainties ($1\,\sigma$ from the assumed Gaussian distribution in log-scale) described as $\sigma_{\log T_{\rm obs}}, \sigma_{\log L_{\rm obs}}$. In this first released version, we follow the IDL code used in Pascucci et al. (2016), where we assume log-uniform priors for T and L in this likelihood function. This is because both initial mass function of stars and their evolutionary timescales imply that the occurrence of stars decreases as a function of $T_{\rm eff}$ and $L_{\rm bol}$. Different likelihood function with different priors can be added in the future versions.

We choose $T_{\rm eff}$ and $L_{\rm bol}$ to estimate the stellar age and mass because extinction is significant for young stars, especially when embedded in the natal cloud. Although the $T_{\rm eff}$ and $L_{\rm bol}$ are not directly observed quantities, they are the two main quantities that evolutionary models can be compared with. When medium or high-resolution spectroscopy is employed on individual targets, $T_{\rm eff}$ and $L_{\rm bol}$ can be well determined, and the best estimates for YSOs are from works where a stellar spectrum is fitted simultaneously with extinction and accretional heating (e.g., Alcalá et al., 2017). To ensure the best results, we recommend using $T_{\rm eff}$ and $L_{\rm bol}$ (with their uncertainties) that are derived simultaneously through spectroscopy.

Our method uses a combination of the pre-main-sequence non-magnetic evolutionary tracks from Feiden (2016) and Baraffe et al. (2015) for hot ($T_{\rm eff} > 3,900$) and cool stars ($T_{\rm eff} \leq 3,900$), respectively. This aligns with the choice as initially suggested in Herczeg & Hillenbrand (2015) and Pascucci et al. (2016), who used the combination of these tracks to derive the stellar masses of Chamaeleon I YSOs, and has also been tested and adopted in some recent works (e.g., Fernandes et al., 2023; Manara et al., 2023; Simon et al., 2019). `ysoisochrone` also has a new algorithm to find the zero-age main sequence (ZAMS) automatically so that post-main-sequence tracks are not included when interpolating to a finer grid of evolutionary tracks (e.g., Fernandes et al., 2023). This algorithm also enables `ysoisochrone` to handle other stellar evolutionary models that are not only focused on pre-main-sequence stars, such as PARSEC tracks (Bressan et al., 2012). We note that there has been recent development on the stellar evolutionary models, but some of those updated models have not yet been released to the public. Therefore, user-developed evolutionary tracks can be also utilized in `ysoisochrone` when provided in the specific format described in the code documentation. We also aim to include those updated models once they are publicly available.

We also provide two other ways to estimate the stellar masses and ages from these isochrones.

1. In some cases, when a good measurement of the stellar luminosity is unavailable, we provide an option to set up the assumed age and then derive the stellar mass. Some examples when this method is useful include: targets that are very young and exceptionally bright; and targets with an edge-on disk so that the stellar $L_{\rm bol}$ is significantly underestimated.

2. The classical method that finds the closest point from the isochrones for each YSOs based on their $T_{\rm eff}$ and $L_{\rm bol}$. We note that this standalone function is primarily used for verification purposes against literature (e.g., Manara et al., 2023; Pascucci et al., 2016) as it does not provide uncertainties.

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