

# Inferring stellar ages by combining isochrone fitting with gyrochronology

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## ABSTRACT

The ages of main sequence stars are difficult to infer because their outward appearances change subtly and slowly during their hydrogen burning lifetimes. In the era of *Gaia*, where precise parallaxes are available for millions of stars, isochrone fitting can be used to provide a constraint on stellar ages. In addition, for those stars with observed rotation periods, gyrochronal ages may also be available. By combining two sets of observable stellar properties and dating methods that are sensitive to different evolving processes in stars, it may be possible to infer more precise and accurate ages than using either method in isolation. In this investigation, the spectroscopic properties of main sequence stars ( $T_{\text{eff}}$ ,  $[\text{Fe}/\text{H}]$  and  $\log g$ ) are combined with their *Kepler* rotation periods, using a hierarchical Bayesian model, to infer their ages as predicted from *both* stellar evolution models and gyrochronology. This is a pilot study, not aiming to produce a state-of-the-art dating model, rather to explore the process of combining two heterogeneous dating methods. Combining two heterogeneous dating methods can illuminate flaws in one or both, although without ground truth it can be difficult to identify the cause of inconsistencies. Although calibration is not the main purpose of this exploratory investigation and the parameters of our gyrochronology model are fixed, only a slight modification to our algorithm would be required to perform a calibration.

## 1. Introduction

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The formation and evolution of the Milky Way (MW) and the planetary systems within it are two topics of significant interest to the astronomical community today. Both of these fields require precise and accurate ages of thousands of stars. Advances in galactic archaeology have already been made, using the ages of red giant stars, some derived from asteroseismology and some from spectroscopy, to probe the age distribution of the MW. Red giants are highly luminous and can be observed to great distances, thus providing age information on the scale of tens of kilo-parsecs. Main sequence stars, although fainter are more numerous and their ages may provide new insights into the formation and evolution of the Solar neighborhood.

Stellar ages provide the key to understanding the evolution of all astrophysical objects. For main sequence (MS) stars however, age is a difficult property to infer. This is predominantly because hydrogen burning stars do not change appreciably during their time spent on the MS: a star like the Sun will grow in luminosity by around a factor of two before becoming a red giant. Luminosity is therefore not a very sensitive probe of age. As explained further later in this paper: the Sun’s rotation period will vary by almost an order of magnitude over its MS lifetime, thus rotation period is a much more sensitive age proxy than luminosity or temperature.

In addition to the difficulties imposed by the slow timescale for variability within MS stars, different dating methods often produce inconsistent predictions for the age of a star. For example, an asteroseismic age will not necessarily agree with a isochronal or rotational age. This is in part because the underlying processes generating the evolution of the observable properties are different and in part because our understanding of the underlying physics is flawed or incomplete. The various available dating methods can be categorised by the underlying physical process they trace. For example, evolutionary models track the radial extent of the hydrogen-burning core and age-rotation relations model the evolving state of the internal magnetic dynamo. In addition, dating methods can be classified by their level of empiricism, *i.e.* the number of free parameters that need to be tuned when fitting the models to the data. The physics behind the evolving luminosity and effective temperature of a star as a result of core hydrogen burning is, for example, very well understood and does not need calibrating; physics determine these models. On the other hand, magnetic activity evolution is poorly understood and must be calibrated using available data. In table ?? we provide an overview of various dating methods, the main observables associated with them, the underlying physics driving the changing observables, the types of star the method applies to and the empirical or physical nature of the model.

### 1.1. Rotation-Dating

Main sequence (MS) stars comprise the majority of our galaxy but their ages are notoriously difficult to measure. Their positions on the HR diagram don’t change significantly during their hydrogen burning lifetimes, a fact that is convenient for life on Earth but inconvenient for galactic archaeologists. Now, due to the abundance of rotation periods for MS stars provided by *Kepler* and to-be provided by TESS, LSST and Wfirst, rotation-dating is the most readily available, precise method for inferring stellar ages. Rotation-dating works well for young stars but a question mark still hangs over its accuracy for stars older than the Sun. Recent results show that old *Kepler* asteroseismic stars rotate more rapidly than expected given their age (*e.g.* Angus et al. 2015; van Saders et al. 2016; Metcalfe et al. 2016). This has been attributed to an evolving magnetic dynamo: as stars reach a critical Rossby number (the ratio of rotation period to the convective overturn timescale), their magnetic field ‘switches off’ and stars maintain a consistent rotation period after that time. Whilst this physical explanation produces a model that fits the data, it is driven by observations, not theory, and other explanations could provide an answer. The data sets typically used to test the age-rotation relations are highly heterogeneous and each set has its own detection and selection biases. For example, asteroseismology favours quiet stars whereas rotation periods are easiest to measure for active stars.

The phenomenon of magnetic braking in MS stars was first observed almost fifty years ago by Skumanich (1972) who observed that the rotation periods of the Sun and young cluster stars seemed to decay with the square-root of time. Later, a mass-dependence was added to the relation between age and rotation period — less massive stars lose angular momentum faster than more massive ones. Kawaler (1988) derived a formalism for this angular momentum loss and his relation depended on the mass loss rate, the .... More recently, Barnes (2003) demonstrated that a simple relation could be used to describe ‘gyrochronology’, the method of rotation-dating, and further works (*e.g.* Barnes 2007; Mamajek and Hillenbrand 2008; Barnes 2010; Meibom et al. 2011), continue to demonstrate that the relation between rotation period and age holds true while theorists (*e.g.* Matt et al. 2012; Epstein and Pinsonneault 2014) modify and extend the efforts to produce physical models of this phenomenon.

Not only do a number of dating methods exist, several different models are often available for the same dating method. In the case of rotation-dating...

## **1.2. Stellar Evolution models**

The ongoing physical processes in the core of a star is reflected externally by an increase in luminosity and temperature. As hydrogen is converted to helium via nuclear fusion in the core, the mass fraction, etc, etc. Leading to etc, etc.

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