A coherent and comprehensive dating system for stars in the Milky Way

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ABSTRACT

Stellar age underpins a wide range of astronomical applications, yet remains one of the most challenging properties to infer. Competing dating methods with different observational inputs often produce wildly inconsistent age estimates. In this work we attempt to combine multiple methods into one coherent model and calibrate that model using galactic dynamics — a well understood physical process. We identify a sample of stars with at least two of the following dating methods available: rotation-dating, isochronal-dating, asteroseismic-dating and dynamical-dating.

1. Introduction

The processes behind the formation of the Milky Way and the objects within it are some of the most elusive and complicated topics in astronomy today, connected by a common theme: stellar ages. Ages provide the key to understanding the evolution of all astrophysical objects, but age is, unfortunately, one of the most difficult stellar properties to measure. Different dating methods often produce inconsistent predictions for the age of the same star. 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 — the radial extent of the hydrogen-burning core or the evolving magnetic dynamo for example. In addition, they can be classified by their level of empiricism, *i.e.* the number of free parameters that need to tuned when calibrating

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these models. The physics behind orbital heating, for example, is very well understood and has only one tunable parameter. On the other hand, magnetic activity evolution is poorly understood and the dating methods that are based on it are often entirely empirical. In table 1 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.

Table 1: A list of all dating methods with the types of stars they apply to and their effective or physical natures.

Method	Observable	Underlying cause	Applicable to...	Effective or Physical model?
Rotation	P_{rot}	Magnetic activity	< 4 Gyr, MS	Effective
Activity	Radio, Hα & X-ray	Magnetic activity	< 5 Gyr, low mass	Effective
Time variability	Time variability	?	?	?
Isochrones	T_{eff}, M_v	Core/shell fusion	Subgiants/giants	Physical (model dependent)
Spectroscopic twins	?	?	?	?
Solar twins	?	?	?	?
Asteroseismology	Frequencies	Core/shell fusion	Old, low mass, Giants	Physical (model dependent)
White dwarf cooling	M_v	Cooling	WDs (& companions)	Physical (1 free parameter)
J_z, J_ϕ, J_r	Position & velocity	Dynamic heating	Disk stars	Physical (1 free parameter)
Galactocentric position	Position	Formation history	All stars	Effective
Coeval pairs	Position & velocity	Disruption	< 1 Gyr, disk	0 free parameters
Open Clusters	Disruption	Positions & velocities	< 2 Gyr	0 free parameters
Exoplanet dynamics	Stability & eccentricity	Interactions	< 500 Myrs	0 free parameters
C/N ratio	C/N ratio	Convective processes	Red giants, A & F	Effective
Chemical abundances	Abundances	ISM enrichment	> 8 Gyr?	Effective
Lithium abundance	L abundance	L depletion	< 500 Myrs?	Effective
$[Y/Mg]$	$[Y/Mg]$	Enrichment	?	Effective
Nuclear isotopes	?	?	?	?
Unusual HRD objects	T_{eff}, M_v	Mergers, ?	Special cases	?
Universe age	All of the above	Finite age of the Universe	All stars	0 free parameters

In this paper we focus on four of these dating methods: rotation, asteroseismology, isochrones and galactic dynamics. A brief overview of each of these methods is provided in below.

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.* **???**). This has been attributed to an evolving magnetic dynamo: as stars reach an 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.* **?**Epstein and Pinsonneault 2014) modify and extend the efforts to produce physical models of this phenomenon.

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

What happens when you can't measure a rotation period? What about the difference in physics that you are investigating?

1.2. Asteroseismology

1.3. Isochrones

1.4. Galactic Dynamics

This paper is laid out as follows. In §2 we describe the data used to calibrate our new model, which is described in §3. In §4 we present a new catalogue of ages.

2. Data

We assembled a sample of stars that have at least two of the four dating methods available. Our main asteroseismic sample targets comprise the 500 short cadence *Kepler* prime targets. These stars all have light curves and therefore rotation periods (or potential rotation periods). The majority are also in Gaia DR1, therefore have parallaxes, positions and 2-dimensional velocities, which can provide constraints on their vertical actions. A subset of these stars have spectroscopic information and therefore make excellent isochronal targets. Our main rotation sample is the 2000 stars in both the *Kepler* input catalogue (KIC) and *TGAS*. These stars have potential rotation periods, parallaxes, positions and 2-dimensional velocities. Some of these stars, particularly those with confirmed planets, also have spectroscopic information and could provide isochronal ages. Our main isochronal data set is the intersection of the *APOGEE* and *RAVE* catalogues with *TGAS*. Relatively precise isochronal ages can be inferred from the spectroscopic stellar properties of these stars, the majority which have ages from *the cannon* (**??**). They also have *Gaia* parallaxes, positions and proper motions as well as radial velocities, providing vertical actions calculated from the full 3-dimensional phase-space.

Table 2: A summary of the data sets used in this project

Sample	Catalogue intersection	Methods available
Asteroseismic	**?** & TGAS	Asteroseismology, rotation, isochrones, dynamics
Rotational	KIC & TGAS	Rotation, isochrones, dynamics
Isochronal	RAVE, APOGEE & TGAS	Isochrones, dynamics

3. Method

In order to establish the level of inconsistency between dating methods, we first compare predictions for each of the above data sets. This is purely an illustrative test as these dating methods are not always independent, for example many rotation-dating models are calibrated using asteroseismic age predictions. For the asteroseismic sample we find that

4. Results and Discussion

5. Conclusions

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