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 ($T_{\rm eff}$, [Fe/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. We provide open source code that calculates stellar ages from spectroscopic parameters and/or apparent magnitudes, and rotation periods.

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 recently 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 are also of great interest for studying the formation and evolution of planetary systems. Almost all exoplanets discovered to date orbit main sequence (MS) stars and it is therefore the ages of MS stars that are needed to capture snapshots of planet evolution. Unfortunately, the very property that makes MS stars good hosts for habitable planets also makes them difficult to date: they do not change substantially over time.

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 turning off the MS. In addition, the Sun's temperature will only increase by around 100 K during its $\sim$8 billion year MS lifetime. Luminosity and temperature are therefore not sensitive proxies for age. On the other hand, Sun's rotation period will vary by almost an order of magnitude over its MS lifetime. Stellar rotation periods are much more sensitive to age than luminosity or temperature. Ages inferred using isochrone fitting use the fact that stars get brighter and hotter over time. Incorporating rotation period measurements into isochrone fitting methods provides additional information that allows for much more precise age inference.

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 categorized 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 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.

The models developed and calibrated by **???** are stellar evolution models and a set of isochrones which include rotation period as an additional parameter. The methodology we presented here is related to these models in that both use a combination of rotation periods and observable properties that track evolution on the Hertzprung-Russel diagram in concert. A major difference is that the gyrochronology model used here is an entirely empirically calibrated one, as opposed to a physically derived one. One major advantage of using a physically motivated gyrochronology model over an empirically calibrated one is the ability to rely on physics to interpolate or extrapolate over parts of parameter space with sparse data coverage. However, rotational spin-down is a complex process that is not yet fully understood and currently no physical model can accurately reproduce all the data available. For this reason, even physically motivated gyrochronology models cannot be used to reliably extrapolate into unexplored parameter space. Although we use a simple version of an empirical gyrochronology model in this work, which, like the physical gyrochronology models, cannot yet reproduce all the observed data, several simple modifications could be made to this model that would produce significant improvements. For example, including and allowing for outliers; stars with anomalously fast or slow rotation periods, could be incorporated into our model.

Due to the abundance of rotation periods for MS stars already provided by *Kepler*/*K2* and the many more expected from future photometric surveys, rotation-dating is one of the most readily available methods 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.

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REFERENCES

R. Angus, S. Aigrain, D. Foreman-Mackey, and A. McQuillan. Calibrating gyrochronology using Kepler asteroseismic targets. *MNRAS*, 450:1787–1798, June 2015. doi: 10.1093/mnras/stv423.

S. A. Barnes. On the Rotational Evolution of Solar- and Late-Type Stars, Its Magnetic Origins, and the Possibility of Stellar Gyrochronology. *ApJ*, 586:464–479, March 2003. doi: 10.1086/367639.

S. A. Barnes. Ages for Illustrative Field Stars Using Gyrochronology: Viability, Limitations, and Errors. *ApJ*, 669:1167–1189, November 2007. doi: 10.1086/519295.

S. A. Barnes. A Simple Nonlinear Model for the Rotation of Main-sequence Cool Stars. I. Introduction, Implications for Gyrochronology, and Color-Period Diagrams. *ApJ*, 722:222–234, October 2010. doi: 10.1088/0004-637X/722/1/222.

C. R. Epstein and M. H. Pinsonneault. How Good a Clock is Rotation? The Stellar Rotation-Mass-Age Relationship for Old Field Stars. *ApJ*, 780:159, January 2014. doi: 10.1088/0004-637X/780/2/159.

S. D. Kawaler. Angular momentum loss in low-mass stars. *ApJ*, 333:236–247, October 1988. doi: 10.1086/166740.

E. E. Mamajek and L. A. Hillenbrand. Improved Age Estimation for Solar-Type Dwarfs Using Activity-Rotation Diagnostics. *ApJ*, 687:1264–1293, November 2008. doi: 10.1086/591785.

S. P. Matt, K. B. MacGregor, M. H. Pinsonneault, and T. P. Greene. Magnetic Braking Formulation for Sun-like Stars: Dependence on Dipole Field Strength and Rotation Rate. *ApJ*, 754:L26, August 2012. doi: 10.1088/2041-8205/754/2/L26.

S. Meibom, S. A. Barnes, D. W. Latham, N. Batalha, W. J. Borucki, D. G. Koch, G. Basri, L. M. Walkowicz, K. A. Janes, J. Jenkins, J. Van Cleve, M. R. Haas, S. T. Bryson,

A. K. Dupree, G. Furesz, A. H. Szentgyorgyi, L. A. Buchhave, B. D. Clarke, J. D. Twicken, and E. V. Quintana. The Kepler Cluster Study: Stellar Rotation in NGC 6811. *ApJ*, 733:L9, May 2011. doi: 10.1088/2041-8205/733/1/L9.

T. S. Metcalfe, R. Egeland, and J. van Saders. Stellar Evidence That the Solar Dynamo May Be in Transition. *ApJ*, 826:L2, July 2016. doi: 10.3847/2041-8205/826/1/L2.

A. Skumanich. Time Scales for CA II Emission Decay, Rotational Braking, and Lithium Depletion. *ApJ*, 171:565, February 1972. doi: 10.1086/151310.

J. L. van Saders, T. Ceillier, T. S. Metcalfe, V. Silva Aguirre, M. H. Pinsonneault, R. A. García, S. Mathur, and G. R. Davies. Weakened magnetic braking as the origin of anomalously rapid rotation in old field stars. *Nature*, 529:181–184, January 2016. doi: 10.1038/nature16168.