Measuring stellar ages with vertical kinematics

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ABSTRACT

Using the proper motions and positions of CH4NG3M3! main sequence *Gaia* and *Kepler* targets with previously measured rotation periods, we demonstrate that gyrochronology age increases with vertical action dispersion. We calculate the ages of the CH4NG3M3! stars with previously published rotation periods that also feature in the TGAS (Tycho-Gaia Astrometric Solution) database using a simple gyrochronology relation. We also estimate the vertical actions of these stars from their two-dimensional TGAS proper motions and parallax. Using radial velocity measurements obtained for a subset of these stars, we demonstrate that the vertical actions calculated from the two-dimensional proper motions are adequately estimated due to the specific orientation of the *Kepler* field. We demonstrate that the gyrochronal ages of these stars scales with vertical action dispersion. We show that the vertical action-age relations vary with stellar mass. This could either reflect the different ages of the different stellar populations, or could be the result of an error in the gyrochronology relations. Further, we show that the relation between vertical action and age does not strongly depend on the specific gyrochronology model used to infer age. Why is this? Radial velocities of these stars, to be published in the second *Gaia* data release should further clarify the relationship between gyrochronology age and vertical action.

1. Introduction

Age is one of the most elusive stellar parameters, particularly for stars on the main sequence. Isochrone fitting methods suffer from poor precision, especially when only photo-

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metric information is available, and asteroseismology is limited to a small sample of bright *Kepler* short cadence targets. Stellar rotation is often used to infer ages via gyrochronology, however it remains relatively untested at old ages due to the sparsity of precise data. The data in hand tell an intriguing story: they indicate that magnetic braking may cease altogether for old, slowly rotating stars. Here we investigate another dating method: galactic kinematics.

Over the last few decades, observations of Milky Way stars with a range of ages have revealed that older stars have greater velocity dispersions than younger stars (*e.g.* **??**). It is hypothesized that interactions between stars and spiral arms or massive gas clouds cause orbital heating and over time the mean velocity of a star will, on average, increase. Velocity however is not time invariant: it depends a star's orbital phase – for example whether it is closer to pericenter or apocenter. On the other hand, action angles *are* time invariant. The action of a star is its angular momentum integrated over the Milky Way potential (no integration would be necessary if the MW were a point mass at the galactic center) and this is constant no matter what orbital phase you happen to observe a star at. For this reason we use the age-action dispersion relation J., Bensby T., We calculate the dispersion in vertical action for Gaia DR1 targets in the *Kepler* field. Although expected to be a weak tracer of age, vertical action dispersion should be an accurate one as the underlying physical processes are relatively simple and well understood. We test the potential of vertical action dispersion as a clock, by comparing age predictions to asteroseismic ages. Using the rotation periods of *Kepler* stars we also test the gyrochronology relations: does magnetic braking cease at late ages?

The processes behind the formation of the galaxy and the formation of exoplanets are two complex topics in astrophysics connected by a common theme: stellar ages. Main sequence (MS) stars comprise the majority of our galaxy but unfortunately their ages are notoriously difficult to measure (see **?**, for a review). 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 has the potential to be the most readily available precise method for inferring stellar ages. Rotation-dating works well for young stars but its accuracy is questionable for stars older than the Sun: old *Kepler* asteroseismic stars rotate more rapidly than expected given their age (Angus et al. 2015; van Saders et al. 2016; Metcalfe et al. 2016). van Saders et al. (2016) attribute this 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 constant rotation period after that time. 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. Here, we test the age-rotation relations by comparing rotational (gyrochronal) age with dynamical age. Data from the first *Gaia* data release (DR1) provides kinematic ages for several MS *Kepler* stars with detectable rotation periods. We use these kinematic ages to test the gyrochronology relations at all ages.

1.1. The status of gyrochronology

The phenomenon of magnetic braking in MS stars was first observed almost fifty years ago by Skumanich (1972) who noticed that the rotation periods of the Sun and young cluster stars decayed with the square-root of time. Kawaler (1988) derived a formalism for this angular momentum loss. 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), demonstrated that the relation between rotation period and age holds true while theorists (*e.g.* Matt et al. 2012; Epstein and Pinsonneault 2014; van Saders and Pinsonneault 2013; **?**) modify and extend physical models that reproduce the observations.

As discussed above, the performance of the age-rotation relations for old stars was recently called into question (Angus et al. 2015; van Saders et al. 2016; Metcalfe et al. 2016). A simple straight-line model for rotational age does not reproduce the ages predicted by asteroseismology for stars older than the Sun. This phenomenon is attributed to a transitioning magnetic dynamo at a critical Rossby number, *Ro*, of 2.6, the solar value (van Saders et al. 2016). As rotation periods slow, *Ro* decreases until it hits the critical value and magnetic braking switches off: stars maintain their rotation period from that point onward. This restricts the applicability of gyrochronology to young, rapidly rotating stars only. This hypothesis is supported by the existing data, however these data are sparse — the analyses demonstrating the discrepancies were conducted on the small number of main sequence, Solar-like oscillators observed by Kepler in short cadence mode with detectable rotation periods: a sample size of around 20. A larger sample of old main sequence stars with precise ages is required to confirm and further characterize the Rossby saturation mechanism introduced by (van Saders et al. 2016). However, old main sequence stars are difficult to age-date with any other method than asteroseismology. We use the age gradients in the kinematic properties of stars to investigate the van Saders et al. (2016) model.

1.2. Kinematic ages

The age-velocity dispersion relations are based on relatively simple physics. There is evidence to suggest that stars in the Milky Way form in the thin disc of the galaxy with relatively small vertical velocities and angular momenta add citations. As time passes these stars are scattered via close encounters with other stars and interactions with galactic spiral arms. The more time passes, the more scattering events, and stars slowly accumulate angular momentum in the vertical direction, known as vertical action. This results in a slow heating of stellar orbits. Older stars can be identified in Gaia DR1 by integrating their orbits in the potential of the Milky Way to convert their proper motions, positions and parallaxes into vertical actions. It is the *dispersion* in vertical action that truly traces age, far better than vertical action itself. However for single stars only the individual's vertical action is available. Nonetheless, J_z^2 increases over time for any given star, and is a weak tracer of age.

2. The Data

- TGAS - Kepler rotators
- TGAS - Asteroseismic giants
- TGAS - Asteroseismic dwarfs/subgiants

3. The Method

- Vert action (JZ) RMS as a function of age for various age indicators.

  - Barnes (2007), (2010)/Mamajek & Hillenbrand (2008)/ Angus (2015) /Matt (2012)/ van Saders (2013)/ van Saders (2016).

- Some understanding of how much we need to know RV to do this right.

  - Simulate results with random RVs

- Use of this to cross-calibrate different age indicators.
- Some understanding of how sensitive we are to crazy selection.

  - Seismology, rotation, TGAS, Kepler.

- Comments on prospect for using JZ as an age indicator directly.

  - What precision?

4. Results and Discussion

5. Conclusion

This research was funded by the Simons Foundation. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate.

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This preprint was prepared with the AAS LaTeX macros v5.0.