The ages and rotation rates of stars across the Milky Way with the Vera Rubin Observatory

1 Introduction

The rotation rates of main-sequence (MS) stars reveal their ages via 'gyrochronology' (rotation-dating), and LSST will provide unprecedented access to the rotation periods, and thus ages, of around 10 billion MS stars out to (unextincted) distances of around 70 kpc. The ages of stars across the Galaxy will allow us to study the formation and assembly history of the Milky Way in exquisite detail. *Mapping the Milky Way is one of the primary goals of the LSST, and our project will enhance Galactic LSST science by capitalizing on the unique opportunity to measure gyrochronal ages from LSST light curves.*

The ages of stars are notoriously difficult to measure using classical techniques, and few reliable and precise stellar ages have been measured to date. However, recent breakthroughs in gyrochronology provide a new opportunity to measure precise ages for MS and subgiant stars with uncertainties as small as 10-20% [Epstein and Pinsonneault, 2014, Angus et al., 2015, van Saders et al., 2016, Angus et al., 2019, 2020, **?**]. All that is needed to infer gyrochronal ages are stellar rotation periods, which can be measured from precise time-series photometry, and apparent magnitudes in two or more band-passes [Angus et al., 2019]. With its deep-fast-wide survey strategy, the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory (VRO) will provide multi-band time-series photometry for billions stars across the Galaxy, and presents an opportunity to revolutionize the field of Galactic archaeology with a large catalog of precise ages. **We propose to maximize the LSST's impact on Galactic astrophysics by measuring precise stellar rotation periods and gyrochronal ages for main-sequence stars across the Galaxy.**

Gyrochronology provides the *best* opportunity to measure the ages of MS stars with LSST. The alternative precise dating method, asteroseismology, will not be accessible for MS stars as their oscillations are too low-amplitude and high-frequency (with periods of a few minutes) [*e.g.* Chaplin et al., 2014]. Gyrochronology is always applicable to fainter, more distant stars, that are observed less frequently, than asteroseismology. The oscillations of red giant stars can have large amplitudes and low frequencies, and many red giants may be characterized and dated with LSST. However, MS stars are much more common that red giants, and they include the lowest-mass, oldest, and youngest stellar populations. In addition, all red giants within a few tens of kpc will saturate LSST's detector; MS stars will be needed to provide ages in the Galactic disk and inner stellar halo, and to connect local and distant parts of the Galaxy. *LSST-gyrochronology provides the best opportunity for a large-scale stellar age study across a large dynamic range of Galactic distances this decade.*

LSST will provide rotation periods for fainter, more distant, redder and older stars than ever before, and will revolutionize the field of stellar rotation as well as Galactic astrophysics. However, one of the main challenges for measuring rotation periods from LSST data will be aliasing. Due to its sparse cadence, stars with periods shorter than around 10-15 days will often be mistaken for slowly rotating stars. Without correcting for this phenomenon, as many as 50% of F and G star LSST rotation periods will be highly inaccurate. We will develop a data-driven method to identify inaccurate aliased period measurements. This method will use the colors, magnitudes and temperatures of stars, as well as the range of variability in their light curves, to predict whether the period measured is likely to be an alias. These potential aliases will be flagged in our final catalogs.

LSST will observe in six filters, so rotation periods must be measured using multi-band techniques. We will use a fast multi-band periodogram to measure rotation periods quickly [VanderPlas and Ivezić, 2015], but will also develop and test a multi-band Gaussian process (GP) method. This

GP method will model quasi-periodicity, which is an important feature of stellar light curves, especially when light curves are much longer than rotation periods [Angus et al., 2019]. Our *multi-band* GP method, which will measure the rotation periods of stars using all 6 LSST bands, simultaneously, will be the state-of-the-art technology for LSST rotation studies, but will come at a computational cost. We will combine periodogram and GP methods to balance speed and accuracy in our final catalogs.

Our multi-band GP and alias-detection methods will be tested on data from the Zwicky Transient Facility (ZTF). ZTF light curves are similar to LSST light curves: they are long, with a sparse observing cadence, in multiple photometric bandpasses. ZTF also offers an opportunity to measure millions of new stellar rotation periods and ages out to distances of around 10 kpc. Once our methods are tested and optimized, we will construct a small-scale rotation period catalog with ZTF data (containing around 100,000 new ages and rotation periods). We will prioritize three types of ZTF targets that will drive forward Galactic archaeology and stellar astrophysics. In order of priority, our ZTF catalog will contain rotation periods for: 1) stars in old open clusters 2) stars with spectra from ground-based surveys, and 3) stars in the stellar halo of the Galaxy. ZTF is complementary to LSST because it covers much of the Northern hemisphere: together, LSST and ZTF will provide ages and rotation periods across most of the sky. It also provides ideal testing ground for our larger LSST study and offers an opportunity to hone our techniques in preparation for the first LSST data release. The rotation periods measured in this ZTF pilot-study will also improve our gyrochronology model, making it LSST-ready.

After the first LSST data release (scheduled for 2024, year three of this five-year project), we will apply our new tools to measure an expected 500,000-1,000,000 new rotation periods and ages for stars in the Galactic disk and halo with LSST. We will target stars in known coeval stellar populations: including open and globular clusters, stellar streams, and merger remnants (*e.g.* Gaia-Enceladus), to measure the ages of these populations and explore stellar rotation in these exotic environments. We will also target stars spread across the stellar halo – particularly K and M dwarfs which reveal the ages of the oldest populations. **We will produce a final catalog of around 500,000-1,000,000 new rotation periods and ages (with 20% uncertanties) for main-sequence FGKM stars, out to 70 kpc, with LSST.**

This is a computationally intensive project but, with the resources available at the Flatiron Institute, we have more than enough computing power to complete it. However, if necessary we will develop machine-learning emulators to enhance the computational efficiency of our model. Our final LSST catalog will include just a small fraction of the billions of available rotation periods and ages with LSST. However, all of our code will be provided as open-source and thoroughly documented as an explicit deliverable of this project. The astronomical community will be able to repeat our analysis for their own target list, using exactly the same procedure. We have a track-record of providing open source software: we have developed and maintain eight different software packages that are related to measuring stellar ages and rotation periods, including the only publicly available gyrochronology package [Angus et al.].

We have calibrated a state-of-the-art gyrochronology model which is, to the best of our knowledge, the *only* model suitable for spectral types F through to M, and ages from 0-10 Gyr. Other gyrochronology models are only calibrated down to K dwarfs and to ages of around 6 Gyr. However, M dwarfs are *essential* for studying the oldest stellar populations in the Galaxy because only M dwarfs remain active for up to 10 Gyr or more. Over the course of this project, we will continue to make improvements to this model. In particular, we will use the results of our ZTF rotation study to improve our gyrochronology relation for M dwarfs and metal poor stars.

Public awareness of science has never been as important as it is now, and evidence suggests that narrative-based scientific communication is most effective. brief summary of broader impact.

2 Measuring rotation periods with LSST and ZTF

Measuring precise stellar ages will revolutionize Milky Way studies, but we cannot measure gyro-ages without first measuring rotation periods. In addition, rotation periods are useful measurements in their own right, and can reveal the physics of stellar magnetism and evolution. The success of this project therefore hangs on our ability to measure accurate rotation periods from LSST data.

LSST and ZTF provide both unique opportunities and challenges for stellar rotation. In this section, we describe how naively measuring rotation periods from sparse light curves can lead to significant contamination from aliasing. We describe how our data-driven method for identifying aliased and spurious signals will signifantly improve the accuracy of LSST rotation periods. We also demonstrate a new multi-band Gaussian process method that will improve the accuracy of rotation periods measured from LSST's long light curves.

Rotational variability in stellar light curves is caused by magnetically active regions on the surfaces of stars: bright, hot faculae and dark, cool spots. As stars rotate, these magnetic regions move in and out of view, generating variability in stellar light curves. This variability is usually periodic, with a period corresponding to the rotation period of the star. The periods of F, G, K and M stars are usually between 0.5-150 days [McQuillan et al., 2014, Newton et al., 2016]. However, rotation periods are strongly mass and dependent: K and M dwarfs rotate more slowly than F and G dwarfs, on average, and old stars rotate more slowly than young stars. The rotation periods of stars are measured by applying period detection algorithms to light curves, for example: Lomb-Scargle periodograms [*e.g.* Reinhold et al., 2019]; autocorrelation functions [McQuillan et al., 2014]; wavelets [García et al., 2014]; phase-dispersion-minimization [Stellingwerf, 1978, **?**]; and Gaussian processes [Angus et al., 2018].

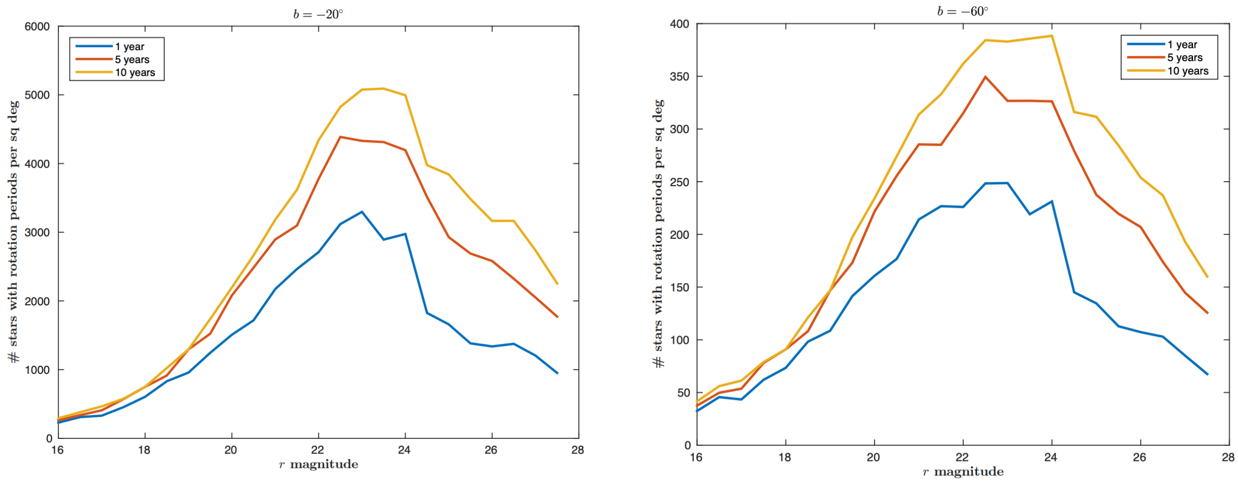
To establish the potential of LSST for stellar rotation, and predict rotation period yields, we conducted injection and recovery experiments. The results of these experiments are described in Angus [2016], and in two community-lead LSST reports: Hawley et al. [2016], Najita et al. [2016]. We injected realistic stellar-rotation signals into simulated LSST light curves, and recovered the periods using Lomb-Scargle periodograms. We used the TRILEGAL model of the Galaxy to simulate a realistic mass and age distribution of stars, and then assigned rotation periods using a gyrochronology model [Angus et al., 2015]. We injected signals using a realistic spot model [Aigrain et al., 2015], with realistic amplitudes, estimated from *Kepler* rotation data [McQuillan et al., 2014], and added LSST-like photometric noise, based on the r-band magnitudes of the targets [Ivezic et al., 2008]. Rotation periods were deemed 'recoverable' if the highest-power peak in the periodogram was within 10% of the injected value.

Figure 1 shows the results of the simulations described above. It shows the expected number of measured rotation periods per square degree as a function of r-band magnitude and survey length. The left panel shows a low-latitude field, and the right panel shows a high-latitude field. Extrapolating over the whole sky, *billions of stars will have measurable rotation periods, even after only one year of LSST observations.* Although, we were able to recover rotation periods for stars as faint as 27th-28th magnitude in this experiment, this is likely to be optimistic. A more realistic faint-limit for LSST rotation studies is 24th-25th magnitude in r-band (corresponding to a G star at 70-100 kpc or an M5 dwarf at 4-6 kpc).

2.1 Dealing with aliasing

One of the major challenges for LSST and ZTF will be aliasing. Some stars, especially hot F and G stars, rotate rapidly, and these rapid rotation periods, combined with the sparse cadence of LSST/ZTF, causes aliasing. As a result, incorrect rotation periods are often measured. No matter

Figure 1: The expected LSST rotation period yield as a function of r-band magnitude and survey length. The left and right panels show the expected number of rotation period detections at low and high Galactic latitudes, respectively. Extrapolation over the entire sky yields billions of rotation period measurements. Figure adapted trom Hawley et al. [2016]. Need to make axis labels bigger.



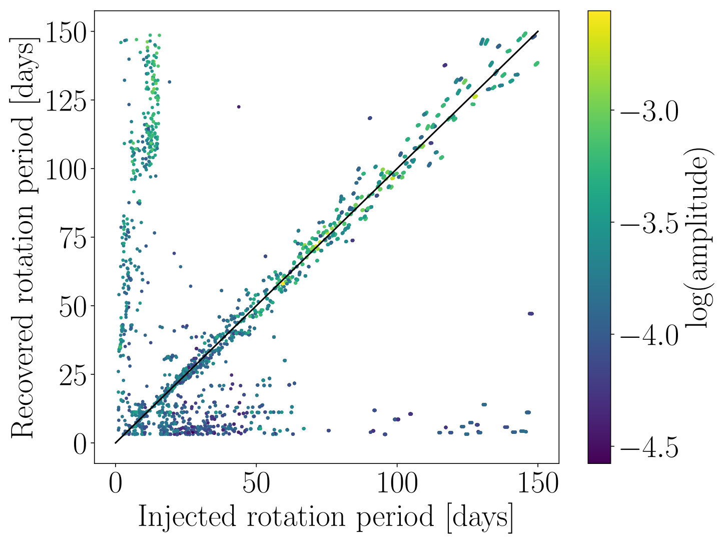
the technique used – periodograms or GPs, this *will be an issue* for LSST/ZTF light curves and any periodic variability study with these surveys will have to deal with this problem. This issue is demonstrated in figure 2 which shows rotation periods measured from simulated LSST light curves[1]. This figure shows the aliasing effect: many stars with true rotation periods shorter than 10-15 days have much longer measured periods.

The most obvious way to skirt this issue would be to avoid stars that are known to have rotation periods shorter than 15 days, for example stars hotter than around 5000 K. However, many cool stars can rotate rapidly too, particularly if they are young. Furthermore, cutting bright F and G stars out of the rotation sample, will limit the maximum distance at which one can measure rotation periods (and thus ages). For these reasons, we will develop a more elegant solution: a data-driven model for detecting and flagging aliases.

The general idea behind this model is that the rotation periods of stars can be approximately determined from their color or temperature, apparent magnitude, proper motion, the amplitude of variability in their light curves, and other simple characteristics. This is because stellar rotation periods either influence or are influenced-by these factors. For example, rotation periods are largely determined by mass and age, hence why gyrochronology is so effective. Rotation period is also related to surface gravity. This is partly because surface gravity is related to age, and age to rotation period, and partly because surface gravity affects a star's moment of inertia. For example, as a star's radius increases along the subgiant branch its rotation period lengthens. The rotation period of a star determines the amplitude of variability in its light curve. This is because rotation generates a magnetic field and the larger the field, the more active regions on the stellar surface and the greater the amplitude of flux-variability. Rapidly rotating stars are therefore highly variable and slowly rotating stars are much less-so. Light curve variability ($R_{\rm var}$) is often parameterized as the 5th-95th percentile range of flux, and it varies by around 3 orders of magnitude. Because they are strongly correlated with rotation period, taken together, color (indicating stellar temperature or mass), absolute magnitude (indicating surface gravity or radius) and $R_{\rm var}$ (indicating magnetic

[1] The LSST cadence model and code for simulating realistic light curves used here is described in Angus [2016] and Aigrain et al. [2015].

Figure 2: Injected vs. measured rotation periods from an injection/recovery test with simulated LSST data. Points are colored by the amplitude of the best-fitting sinusoid. This figure highlights the issue of aliasing – when sparsely sampled, short-period signals can be mistaken for long-period signals. In this example, around 10% of recovered rotation periods are aliases of the true rotation period signal. We will predict aliased cases using data-driven methods like those in our recent study [**?**].



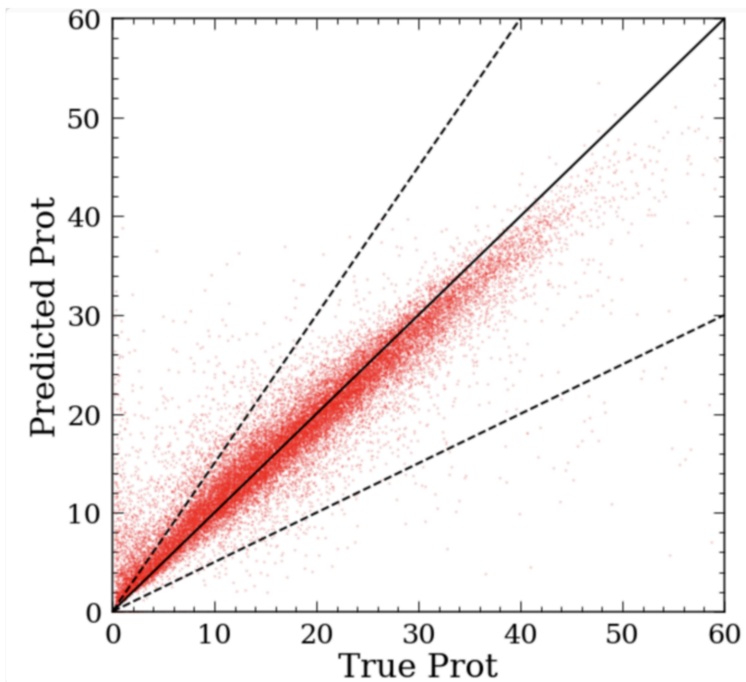
field strength) are powerful predictors of stellar rotation periods.

In **?** we used random forest regression to predict the rotation periods of *Kepler* stars, based on a set of observable features. When trained on *Kepler* data, our method and open-source project, `astraea`, can predict rotation periods to within 10% of the measured value. Figure 3 shows the predicted rotation periods of *Kepler* stars, compared with their directly measured rotation periods. Although originally trained with *Kepler* data, this method could easily be generalized to LSST or ZTF. We would use the apparent magnitudes and colors of stars in LSST/ZTF band-passes, and *Gaia* colors and parallaxes where available. The range of light curve variability, R_{var} would also be used as a feature, however care must be taken to account for chromatic variations in R_{var}.

Although the predictive precision of our LSST/ZTF version would likely be lower than it was with *Kepler*, predicting rotation periods with up to a 50% precision would still suffice for flagging the majority of alias cases. **We propose to train a data-driven model of stars to** *predict* **stellar rotation periods, and thereby flag aliases.** This model will be based on the previous random forest method we developed for *Kepler* data (`astraea`), however it will be designed to be generically applicable to any photometric survey. It will be trained with stellar rotation period measurements and stellar properties from all available stellar rotation catalogs from the *Kepler* TESS and *MEarth* surveys. Stars in these surveys will be mapped to the ZTF and LSST photometric systems with stellar model grids using the `isochrones` software package.

To test and further train this model, we will use a combination of ZTF and TESS data. ZTF and TESS observed the northern sky simultaneously and TESS light curves are suitable for measuring short rotation periods. TESS will reveal aliases in ZTF data – some stars which appear to have long rotation periods in ZTF light curves will actually have rapid rotation periods in TESS light curves. We will measure the rotation periods of 5-10,000 stars observed with both ZTF and TESS.

Figure 3: Measured vs. predicted rotation periods for *Kepler* stars. Our random forest model was trained using the temperatures, magnitudes, colors, velocities, and light curve statistics of stars and learned the correlation between each feature and rotation period. This model predicts rotation periods with a mean precision of 9-13% for *Kepler* stars. We will build a similar data-driven model to predict the rotation periods of ZTF/LSST stars in order to flag erroneous measurements caused by aliasing.



These data will be used to test and further train our data-driven alias detection method.

This novel vetting technique could introduce a non-trivial detection bias in our final catalog of rotation periods and ages. For this reason, this tool will only be used to *flag* potential aliases, not to cut them; the users of our catalog will decide whether to cut aliased candidates or not.

2.2 Stellar rotation with multi-band light curves

Any rotation study performed with LSST or ZTF data must account for the multi-band nature of their light curves. LSST will observe in six bands: u, g, r, i, z, y, and ZTF observes in ZTF-g, ZTF-r, and ZTF-i. The light curves in these different band passes will have different mean magnitudes, determined by the Spectral Energy Distributions (SEDs) of the stars. They will also have different variability *amplitudes*, because stellar variability is chromatic: it is produced by temperature variations across the stellar photosphere. For example, the amplitude of rotational variability will be larger in bluer band-passes, where the contrast between cool spots and hot photosphere is maximal[2].

To measure rotation periods from LSST light curves, it will be necessary to model the variability in each band-pass *simultaneously*, as opposed to averaging or stacking periodograms for individual band-passes [VanderPlas and Ivezić, 2015]. This means that the magnitude offset of each filter (*i.e.* the SED) and the chromatic amplitude of variability must be modeled and marginalized over, as the period is being measured. To measure rotation periods with LSST and ZTF data, we will mainly use a publicly available multi-band periodogram method [VanderPlas and Ivezić, 2015]. This method models the mean magnitude and the amplitude of the signal in each filter, simultaneously, and it is *fast*, taking just 100 ms for a year-long LSST light curve.

The multi-band periodogram method assumes strict-periodicity, however stellar light curves can be highly quasi-periodic [*e.g.* Aigrain et al., 2015]. For this reason, Gaussian processes can provide more significantly more accurate rotation period measurements, at the cost of computational speed [Angus et al., 2018]. Gaussian processes are semi-parametric models that describe the covariance of a time-series, and are ideally suited to quasi-periodic signals. Stellar light curves are quasi-periodic because magnetic surface regions are transient; they have finite lifetimes which are often shorter than the rotation period of the star (which is the case for the Sun). For this reason, quasi-periodic GPs often provide more accurate rotation period measurements than strictly-periodic Lomb-Scargle periodograms [Angus et al., 2018]. We have developed a proof-of-concept version of a multi-band GP for rotation period measurement. We use the `celerite` [Foreman-Mackey et al., 2017], `exoplanet` [Foreman-Mackey and Barentsen, 2019] and `PyMC3` [Salvatier et al., 2016] codes to model time-series with fast GPs and to explore the parameter space with the gradient-based No U-Turn Sampling (NUTS) method. As a result, we are able to measure rotation periods for ZTF light curves in around 1 minute of CPU time. To model the chromaticity of stellar variability, we infer scaling factors that adjust the relative amplitudes of signals in different band-passes. These scaling factors divide out the amplitude differences in the different bandpasses, merging all bands into one unified light curve. This technique can be applied to any filters in any combination, and would therefore allow any time-series surveys to be combined. For example, targets observed by both ZTF and LSST, or both ZTF and TESS could be modeled using all available data. As an added bonus, the inferred mean magnitudes of light curves in different band-passes provide a precise estimate of the star's SED, and the amplitudes may provide a crude estimate of the temperatures of the dominant magnetic surface regions. Figure **??** shows a demonstration of this method, applied to ZTF data.

Until recently, GP inference was prohibitively computationally expensive, however new technology in both linear algebra and MCMC sampling has rendered them tractable [Foreman-Mackey et al., 2017, Foreman-Mackey and Barentsen, 2019, Salvatier et al., 2016]. The sparsity of LSST

[2] For stars that are spot-dominated. Stars that are facula-dominated may be more variable in red band-passes [Montet et al., 2017]

light curves is actually a benefit for GP analysis – keeping computation-time low. Although GP analyses are much faster than they used to be, and could feasibly be applied to thousands or tens-of-thousands of LSST targets, they still take around a few minutes per star (for a fully converged MCMC, although optimization takes just a few seconds). GPs are not always the pragmatic choice when dealing with millions of light curves or more. By simulating stellar variability signals using a realistic spot model, we will determine best-practices for LSST/ZTF: when is a periodogram acceptable and when does a GP approach become essential? For example, it is likely that GP models will be necessary for modeling rotation periods from 10-year LSST light curves, but periodograms may be acceptable for light curves that are 1 or 2 years long.

2.3 Rotation periods with ZTF

To test and develop our multi-band periodogram technique, we will apply it to ZTF light curves. We will also produce a catalog of new rotation periods and ages with ZTF data.

ZTF is a wide-field time-domain survey, an LSST analog, conducted by the Palomar telescope in California [**?**]. ZTF observes in three band-passes: ZTF-g, ZTF-r, and ZTF-i and has a limiting magnitude of around 20 dex in each filter. ZTF is the idea data set to test rotation period detection methods for LSST.

While ZTF does not go as deep as LSST, it is able to observe much brighter stars. ZTF saturates at around 13th magnitude, providing a two magnitude overlap with TESS, which goes down to around 15th. ZTF therefore creates a bridge between TESS and LSST: the three surveys together provide access to the rotation periods of stars from 6th to 24th magnitudes.

ZTF is a transient survey, primarily designed for transient phenomena, not stellar rotation. As a result, the light curves produced by the main survey pipeline are too noisy for rotation period measurements. However, our custom data reduction pipeline produces light curves of a suitable quality for rotation period measurement. We model use simple aperture photometry to extract light curves, and remove systematic noise by modeling the source flux as a linear combination of nearby stars. Figure **??** shows the light curve of a ZTF star, reduced with our pipeline, compared with the light curve produced by the survey pipeline.

More detail on target selection (including clusters) and yield calculations. Describe Jason's ZTF pipeline.

3 Gyrochronology: measuring the ages of LSST and ZTF stars

Better intro here. The ages of stars, especially main-sequence stars are difficult to measure because their temperatures and luminosities change slowly over time [see Soderblom, 2010, for a review of stellar ages]. Fitting isochrones or stellar evolution models to stars' positions on the Hertzsprung-Russell diagram therefore often results in highly imprecise age constrains. This is inconvenient as the majority of stars in the Galaxy are on the main sequence. Fortunately however, the *rotation rates* of MS stars evolve rapidly due to magnetic braking, and can be measured precisely from time-series photometry [*e.g.* McQuillan et al., 2014, Angus et al., 2018, Reinhold et al., 2019]. Incorporating rotation periods, measured from time-series photometry, into age analyses can reduce age-uncertainties by 300-1000% for MS stars [Angus et al., 2019]. Dating stars via their rotation periods is called gyrochronology, and the uncertainties on gyrochronal ages can be as small as 10-20%, rivaling the precision of asteroseismology Epstein and Pinsonneault [2014], Angus et al. [2019].

The rotation periods of FGKM main-sequence stars increase over time due to magnetic braking, and the relationship between rotation period and age can be used to date them [*e.g.* Skumanich, 1972, Noyes et al., 1984, Kawaler, 1988, Pinsonneault et al., 1989, Charbonneau, 2010, Matt et al., 2015]. Stellar rotation periods converge onto a single evolutionary track, often called the 'slow sequence', shortly after they evolve onto the main sequence. After this time, a star's rotation period and temperature or color can be used to infer its age [Kawaler, 1988, Barnes, 2003, Irwin and Bouvier, 2009]. Once converged to the slow sequence, rotation periods generally follow a power law relation in time with an index of $\sim 1/2$ [Skumanich, 1972]. However, new *Kepler* and *K2* rotation periods of stars in open clusters, asteroseismic stars, and stars with kinematic ages, show that the exact value of this power law index varies as a function of mass and age [Angus et al., 2015, van Saders et al., 2016, Curtis et al., 2019, Spada and Lanzafame, 2019, Angus et al., 2020]. It is now clear that stars of different masses and ages spin-down differently. Because of the non-linear and time-variable relation between rotation period and age, the gyrochronology relations cannot be extrapolated to old ages or low masses where little calibration data exist. Instead, they must be *actively calibrated for stars of all masses and ages.*

Most empirical gyrochronology models calibrated to date have been separable power-law relations in $P_{\rm rot}$, age and color [Barnes, 2003, 2007, Mamajek and Hillenbrand, 2008, Meibom et al., 2011, Angus et al., 2015, Meibom et al., 2015, Douglas et al., 2019, Angus et al., 2019]. However, new data show that the gyrochronology relations are complex and cannot be adequately described with age and color-separable models [Angus et al., 2015, van Saders et al., 2016, Agüeros et al., 2018, Metcalfe and Egeland, 2019, Curtis et al., 2019, Angus et al., 2020]. We will therefore use a new *Gaussian process* (GP) gyrochronology relation. A GP model is a good choice for a gyrochronology relation because it is flexible but assumes that rotation periods change smoothly across time and mass. Figure **??** shows an example of what this model will look like for FGK stars. It shows a sample of rotation periods, temperatures and ages of benchmark asteroseismic and open cluster stars (circular points). Filling in the old and low-mass (late G to early M dwarfs) regime is a grid of kinematic ages, calculated for *Kepler* stars (square points). Shown in the upper-right are kinematic ages for *MEarth* stars. The lines (isochrones, or 'gyrochrones') show a new GP-based gyrochronology relation.

An important feature of this model is that it captures 'stalling', a phenomenon that seems to halt the magnetic braking of K dwarfs in $\sim$1 Gyr open clusters [Curtis et al., 2019]. This stalling behavior is captured in the inversion of isochrones/gyrochrones in figure 4 at around 1 Gyr for early K dwarfs (around 5000 K) and at older ages for later K dwarfs [Angus et al., 2020]. This behaviour thought to be caused by angular momentum re-distribution in stellar interiors and a recent set of semi-empirical models, calibrated with open clusters, capture this behavior [Spada and Lanzafame, 2019]. However, those semi-empirical models are only calibrated up to around Solar age, 4-5 Gyr, and only to 4000 K: late K dwarfs. M dwarfs will dominated our LSST/ZTF rotation catalog, so it is essential that we can measure their ages with a gyrochronology model.

The gyrochronology model shown in figure 4 is, to the best of our knowledge the first and only model that is calibrated for M dwarfs and for stars older than the age of the Sun. This is because it is partly calibrated using kinematic ages of field stars.

Better description of calculating kinematic ages. Figure 5 compares kinematic ages with alternative age-dating techniques to demonstrate the accuracy of gyro-kinematic ages. The kinematic age of each comparison star was calculated from the vertical velocity dispersions of *Kepler* stars in the same $P_{\rm rot}$ and $T_{\rm eff}$ bin, using an AVR [Yu and Liu, 2018]. Kinematic age uncertainties are based on Monte Carlo error propagation, and are typically around 1 Gyr. Asteroseismic stars are shown in blue [van Saders et al., 2016], [priv. comm.]. Figure 5 also shows the kinematic ages of two M dwarfs with ages determined from the cooling age of a white dwarf companion [R. Kiman, priv. comm.]. Three old open clusters are shown: NGC 6819 [Meibom et al., 2015], NGC 752 [Agüeros et al., 2018] and Ruprecht 147 [J. L. Curtis, priv. comm.]. We also show a sample of isochrone ages

Figure 4: A demonstration of our new empirical Gaussian process gyrochronology relation. This relation was fit to cluster and asteroseismic stars which provide ages for young and hot stars (circular points), a grid of kinematic ages from the *Kepler* rotation sample which provide ages for cool G and K dwarfs, (square points), and kinematic ages from the *MEarth* rotation sample, providing ages for M dwarfs. The full *Kepler* rotation sample is shown in gray, to illustrate the rotation period distribution of field stars. The Solar data point is also shown.

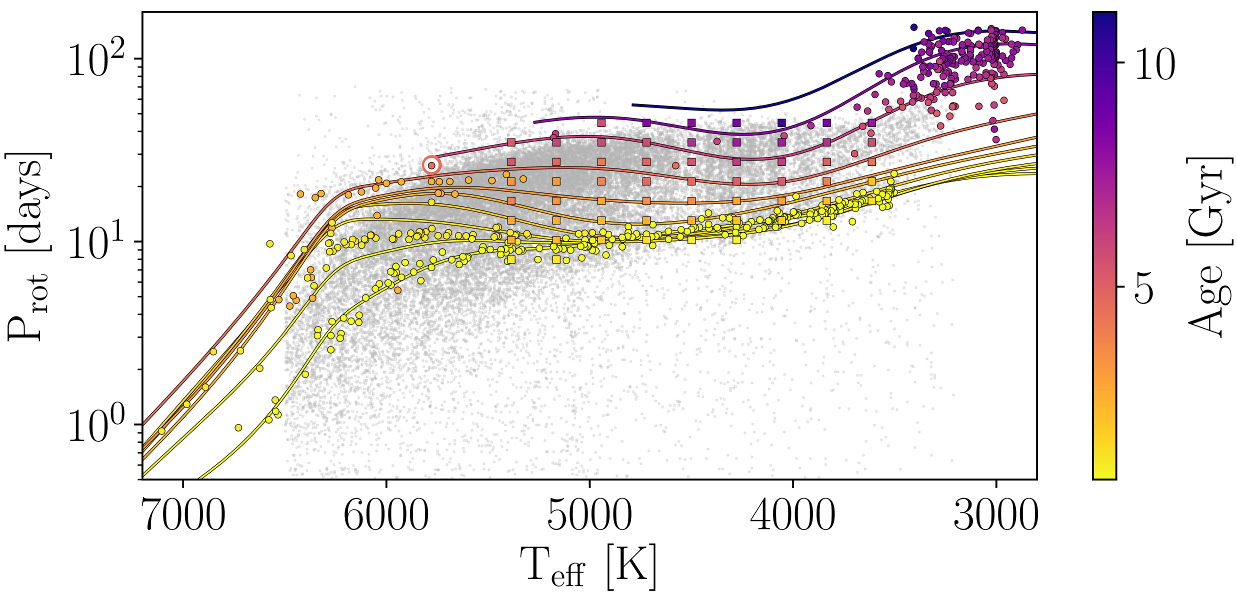
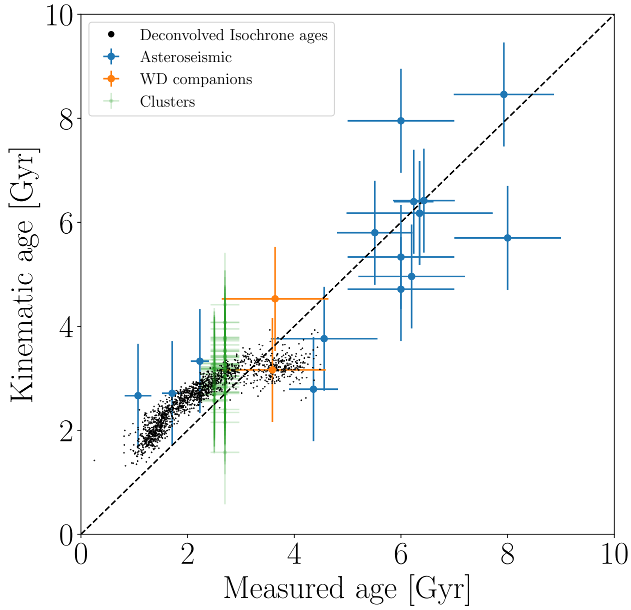


Figure 5: The kinematic ages of stars with independent age estimates. We compared our kinematic ages with independent ages from isochrone fitting, asteroseismic analysis, white dwarf cooling and open clusters. Almost all age measurements are consistent with the kinematic ages.



for *Kepler* F and G field stars[3] [Berger et al., 2020]. These isochrone ages have large uncertainties, so to show a meaningful comparison they have been 'deconvolved' using extreme deconvolution, a method that fits multiple Gaussians to the data, to learn the underlying, noise-free distribution [Bovy et al., 2011]. Almost all of these independent age measurements are consistent with the kinematic ages. This is remarkable given that our only assumptions are that 1) stellar velocities increase over time according to an AVR [Yu and Liu, 2018] and 2) that stars of similar rotation periods and temperatures have similar ages.

3.1 Improving the gyrochronology models

We have laid the groundwork for a unique, sophisticated gyrochronology model that captures the behavior of FGKM stars from 0-10 Gyr. However, further improvements can be made to improve age-accuracy for LSST. For example, in our ZTF rotation period study we will measure the rotation periods of XXX new K and M dwarfs. The kinematic ages of these stars will further improve our gyrochronology relation at low masses. In addition, the LAMOST-Kepler catalog provides metallicities for 10,000 field stars with measured rotation periods. We will use these data to calibrate a metallicity-dependent version of our gyrochronology model. This will become important for stars in the halo, and other Galactic stellar populations with low metallicities.

The gyrochronology model shown in figure 4 is, to the best of our knowledge, the only gyrochronology model that applies to stars cooler than 4000 K, ($M < 0.6\ M_\odot$). The only other model that is valid for K dwarfs is **?**, and that model is not calibrated for M dwarfs. We already maintain open source software for gyrochronology, a *Python* package called `stardate` [Angus et al.]. We will update the gyrochronology model in `stardate` with a GP model like the one shown in figure **??**. That model has two additional features that will be incorporated into our new GP model. It

[3] We only compare isochronal ages for F and G stars as the isochronal ages of K and M dwarfs are not well constrained (their uncertainties are greater than 5-10 Gyr).

accounts for weakened braking, which affects the rotation periods of old F and G stars [van Saders et al., 2016], although this is unlikely to be an issue for LSST/ZTF because it only applies to stars with very low-amplitude rotation signals that are on the cusp of detectability with *Kepler* and therefore unlikely to be detectable with LSST/ZTF (Angus et al, in prep). The *stardate* model also accounts for stochasticity in the rotation periods of young stars. These stars rotate with a range of periods that are not strongly determined by their age. These are stars that have not yet converged on the 'slow sequence' of gyrochronology. Although few FGK stars fall into this category, many M dwarfs do, so this becomes important for these low-mass stars. Once again, to the best of our knowledge, our model is the only gyrochronology model that accounts for the stochastic rotation periods of young stars.

To apply gyrochronology to halo stars, we will need to incorporate metallicity in to our relation. Around 10,000 *Kepler* stars with measured rotation periods and metallicities measured from LAMOST spectra are currently available. We will include metallicity as an additional dimension in our gyrochronology relation, and calibrate it using LAMOST data. We have already calculated kinematic ages for these stars, so this will be a relatively simple task.

3.2 Compution costs

Describe work to speed up computation with machine-learning emulators (just like `astraea`), etc. Describe potential 'tiered' approach to gyrochronology. With fast gyrochronology and LS periodograms, we could potentially produce millions of period and measurements...

4 Exploring the rotation periods and ages of stars across the Galaxy

Describe potential science projects using new age data. In particular, describe contingency plan for LSST delays.

5 Scientific Impact

This section is very-much in progress. Emphasise impact of catalog. Emphasise track-record of open source software. Several astronomical fields will be impacted by the XXX rotation periods, ages, SEDs, spot temperatures, and Q-factors, and ages released in our catalog. Below, we highlight key studies that will be possible with these data:

- **Galactic Archaeology.** The ages of stars in the thin and thick disks of the Galaxy could reveal orbital migration and mixing properties, particularly when combined with spectroscopic metallicity or elemental abundance measurements. Stellar ages of stars in the Galactic disk would reveal the local star formation history. The ages of stars in the stellar halo could reveal the remnants of accreted dwarf galaxies or tidally disrupted globular clusters: coeval stellar populations with similar orbital properties. The ages of these populations would reveal the merger history of the Milky Way, and their dynamic properties could reveal dark matter substructure.
- **Stellar astrophysics.** Stellar rotation periods can reveal the magnetic properties of stars. A gap in the rotation period distribution of stars is thought to be produced by stellar magnetism, etc... When do M dwarfs reach the slow-sequence? The rotation periods of M dwarfs are often omitted from catalogs because they are faint and they typically rotate slowly, which makes them challenging targets for rotation period detection. On the other hand, these stars are ideal rotation targets for ZTF and LSST. The long light curves and irregular, sparse cadence of these surveys are ideal for measuring long rotation periods: the long baselines allow long rotation

periods to be measured, and the sparse cadence ensures computational speed. In addition, M dwarfs remain magnetically active for at least 10 Gyr, so almost all have them are rotationally variable. M dwarfs are also the most highly variable MS stars, and their light curves have large variability amplitudes. M dwarfs are therefore *ideal* targets for rotation and age studies with ZTF and LSST.

To date, only a few thousand M dwarf rotation periods have been measured, including just a few tens of late M dwarfs. However, *VRO will dramatically change this*: with its faint observing limit of 24, the VRO will observe billions of M dwarfs.

- **Exoplanets (populations, characterization and detection.** The radii, orbits and overall occurrence rates of exoplanets are thought to evolve on a range of characteristic timescales [Christiansen et al., 2019]. The ages of planet hosts would reveal physical processes that govern the evolution of exoplanet interiors, atmospheres, and orbital dynamics. In addition, stellar rotation periods are also useful to detect and characterize extrasolar planets. For example, the rotation periods of exoplanet hosts are often used to model RV jitter caused by stellar activity when measuring the masses of exoplanets. A catalog of rotation periods will help planet hunters detect and weigh exoplanets with RV measurements. Stellar rotation periods can also indicate the magnetic activity of host stars, and are useful for modeling high energy flux received by exoplanets.
- **Complementing other data sets.** TESS pixels are large, and TESS exoplanet and stellar rotation studies will suffer from crowding. Both ZTF and LSST will have excellent image resolution – far better than the TESS or *Kepler* missions. A ZTF/LSST rotation period catalog would aid pixel-level source modeling in the TESS and *Kepler* surveys – improving both exoplanet search and rotation period determination.

6 Risk

- What if the photometric precision of LSST light curves is lower than expected and far fewer rotation periods can be measured? Even more of a reason to fully characterize the ability of the LSST to deliver light curves.
- What if the LSST first data release is delayed? We will work on Galactic archaeology studies with ZTF instead. If delayed by two years, we will also study the rotation period gap with ZTF.
- What if the gyrochronology models are significantly wrong for stars outside the Solar neighborhood? We'll probably learn that and adapt the models as we go. But if they're not perfect, that may not be a big deal.

7 Why Us

The LSST will be a powerful tool for stellar rotation and gyrochronology studies, and capitalizing on this unique data set is paramount. With our background knowledge and expertise, previous contributions to the fields of stellar rotation and gyrochronology, and tools in-hand, we are perfectly poised to conduct a rigorous and comprehensive rotation/age study with LSST.

1. We developed and maintain the only open-source gyrochronology code currently available (stardate). [Angus et al., 2019, Angus et al.]
2. We are experts in gyrochronology, and discovered two new phenomena in stellar magnetic braking: weakened magnetic braking [Angus et al., 2015], and 'stalling' [Agüeros et al., 2018, Curtis et al., 2019]. These discoveries have led to major revisions in the theories behind magnetic

braking [van Saders et al., 2016, 2018, Spada and Lanzafame, 2019, Angus et al., 2020].

3. We have calibrated the only gyrochronology relation that extends into the M dwarf regime (see figure 4).
4. We are experts in stellar rotation, and have developed open-source software for measuring rotation periods using a variety of statistical methods [**?**Angus et al., 2016].
5. We pioneered the use of Gaussian processes for measuring rotation periods, and have developed and maintain open-source code for doing so [Angus et al., 2018, **?**, Foreman-Mackey and Barentsen, 2019, **?**].
6. We have developed tools for performing photometry, extracting light curves, and detrending for a variety of time-series surveys, including ZTF, TESS, and *K2*.
7. We have developed fast methods for emulating stellar evolution and gyrochronology models [**?**].

8 Management and Timeline

We have established key milestones for this project and a timeline that will allow us to accomplish the goals of this project over 5 years.

8.1 Timeline

Year 1 (09/21 – 09/22)
- Test rotation measurement on ZTF data.
- Test and develop aliasing identification methods with ZTF (TESS provides ground-truth).

Year 2 (09/22 – 09/23.)
- Roll-out rotation period methods on ZTF data.
- Measure M dwarf periods in NGC 6911 (and NGC6819?).
- First catalog of ZTF ages.

Year 3 (09/23 – 09/24).
- Begin analysis of LSST data and tune methods if necessary.
- Roll-out rotation period methods on LSST data.
- Measure rotation periods in clusters.

Year 4 (09/24 – 09/25).
- Tune gyrochronology relations.
- Measure ages for LSST stars.

Year 5 (09/25 – 09/26).
- Study 1: The ages of halo populations.
- Study 2: The rotation period gap: a Universal phenomenon?

9 Broader Impacts of proposed research

The overall goal of this educational program is to advance public education in astronomy by partnering astronomers with screenwriters, playwrights and authors.

9.1 Partnerships between scientists and artists

Storytelling is a powerful communication tool, which can be used to evoke emotion and stimulate action in an audience. Going beyond a standard science talk: storytelling uses personal narrative, characters and a tangible timeline to evoke emotion and investment from an audience. "Research suggests that narratives are easier to comprehend and audiences find them more engaging than traditional logical-scientific communication." Storytellers achieve engagement by building tension with conflict and mystery. Stories engage audiences and can leave a lasting impression, stimulating reflection which engages the audience and makes them invested – they want to see the resolution and hear how things work out in the end.

Under construction

Results of prior NSF support

None

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