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# Extending the Asteroseismic Calibration of the Stellar Rossby Number

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ABSTRACT

The stellar Rossby number (Ro) is a dimensionless quantity that is used in the description of fluid flows. It characterizes the relative importance of Coriolis forces on convective motions, which is central to understanding magnetic stellar evolution. Here we present an expanded sample of Kepler asteroseismic targets to help calibrate the relation between Ro and Gaia color, and we extend the relation to redder colors using observations of the mean activity levels and rotation periods for a sample of brighter stars from the Mount Wilson survey. Our quadratic fit to the combined sample is nearly linear between $0.55 < \mathrm{G_{BP}} - \mathrm{G_{RP}} < 1.2$, and can be used to estimate Ro for stars with spectral types between F5 and K3. The strong deviation from linearity in the original calibration may reflect an observational bias against the detection of solar-like oscillations at higher activity levels for the coolest stars.

## 1. INTRODUCTION

The stellar Rossby number (Ro) is a key parameter that is related to both the magnetic evolution of stars and the space weather environment of their planetary systems. From an observational perspective, it is traditionally estimated as the ratio of the stellar rotation period to the convective turnover time ($\mathrm{Ro} \equiv P_{\mathrm{rot}}/\tau_c$). While the rotation period can often be inferred directly from observations, the convective turnover time depends on properties of the stellar interior that can only be determined indirectly from stellar models. The most widely used approach to estimate the convective turnover time was developed more than 40 years ago (Noyes et al. 1984). Exploiting the fact that stellar activity levels are correlated with Ro, this approach used the chromospheric activity levels and rotation periods for 41 main-sequence FGK stars observed by the Mount Wilson Observatory (MWO) survey to fit a semi-empirical relation between $\log \tau_c$ and B−V color. However, this relation depends on relatively indirect constraints from stellar evolution models, and yields values of $\tau_c$ for the Sun that are inconsistent with standard solar models.

Recently, a new approach was pioneered using asteroseismic models for 62 stars with solar-like oscillations detected by the Kepler mission to calibrate a relation between $\tau_c$ and Gaia color (Corsaro et al. 2021). This analysis relied on asteroseismology to yield precise values for all of the stellar properties that are required to estimate $\tau_c$ directly, including the depth of the surface convection zone as well as the stellar radius, mass, and luminosity: $\tau_c \simeq d_{cz}(M/LR)^{1/3}$. The approach yields a very good estimate of the local convective turnover time at the base of the stellar convection zone, matching the value for the Sun obtained from a fully calibrated standard solar model (Bonanno et al. 2002). The primary limitation of this relation is the range of Gaia colors for the Kepler asteroseismic sample.

## 2. EXPANDING THE ASTEROSEISMIC SAMPLE

The Kepler mission produced two well characterized samples of asteroseismic targets: the LEGACY sample of solar-type main-sequence stars that were observed in short-cadence for at least 12 months (Lund et al. 2017), and the KOI sample of suspected and confirmed exoplanet host stars with detected solar-like oscillations (Davies et al. 2016). The original calibration of $\tau_c$ as a function of Gaia color only used the LEGACY sample, because the published modeling results for the KOI sample (Silva Aguirre et al. 2015) did not tabulate the depth of the surface convection zone. We compiled the necessary details from a uniform set of modeling results for the LEGACY and KOI samples, which were obtained with v1.3 of the Asteroseismic Modeling Portal (AMP; Metcalfe et al. 2009; Creevey et al.

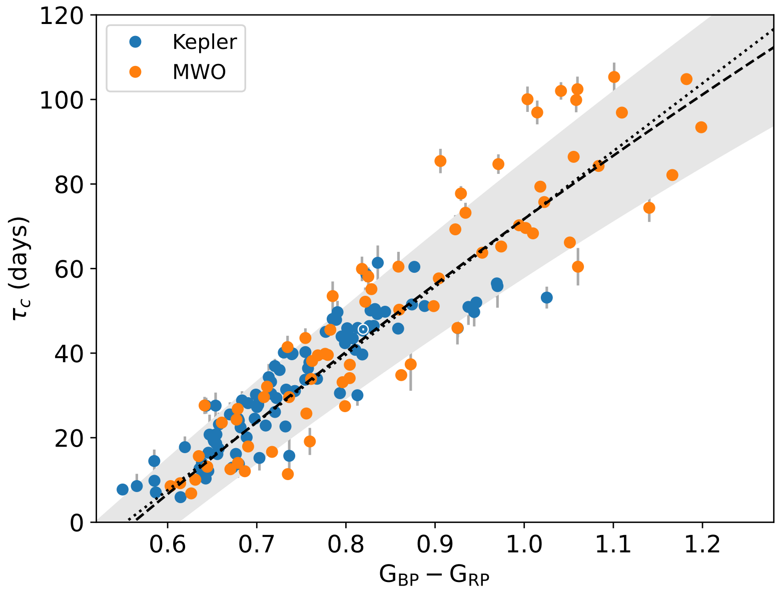


**Figure 1.** Convective turnover time $\tau_c$ as a function of Gaia color for the expanded sample of Kepler asteroseismic targets (blue points) following Corsaro et al. (2021), and inferred for the MWO sample (orange points) from the measured mean activity levels and rotation periods published in Baliunas et al. (1996). The dashed line shows the quadratic fit to the combined sample with the $1\sigma$ credible interval shaded, while the dotted line shows the linear fit for comparison.

2017). This expanded sample increases the total number of stars from 62 to 96, and extends the reddest color from $\mathrm{G_{BP}-G_{RP}} = 0.97$ to 1.02. The resulting values of $\tau_c$ are shown as blue points in Figure 1.

## 3. EXTENDING THE CALIBRATION

For a sample of stars from the MWO survey with well determined mean activity levels $\langle R'_{\rm HK}\rangle$ and rotation periods, Brandenburg et al. (1998) identified a correlation between $\langle R'_{\rm HK}\rangle$ and $\mathrm{Ro}^{-1}$. Inspired by this correlation, we assume that $\langle R'_{\rm HK}\rangle \propto \mathrm{Ro}^{-1}$ and predict $\mathrm{Ro}/\mathrm{Ro}_\odot$ from the inverse of the mean activity level relative to solar: $\mathrm{Ro}/\mathrm{Ro}_\odot \simeq \langle R'_{\rm HK}\rangle_\odot \,/\, \langle R'_{\rm HK}\rangle$. We then use $P_{\rm rot}$ to infer $\tau_c$ from $\mathrm{Ro}/\mathrm{Ro}_\odot$:

$$\tau_c \equiv \frac{P_{\rm rot}}{\mathrm{Ro}} = \frac{P_{\rm rot}}{0.496\,\mathrm{Ro}/\mathrm{Ro}_\odot} \simeq \frac{P_{\rm rot}}{0.496\ \langle R'_{\rm HK}\rangle_\odot \,/\, \langle R'_{\rm HK}\rangle}. \tag{1}$$

Here we have chosen $\mathrm{Ro}_\odot = 0.496$ to anchor our calibration of $\tau_c$ to the asteroseismic scale of Corsaro et al. (2021). Using the measured values of $\langle R'_{\rm HK}\rangle$ and $P_{\rm rot}$ from Baliunas et al. (1996) for the MWO sample, and adopting $\langle R'_{\rm HK}\rangle_\odot$ from Egeland et al. (2017), the results of Eq.(1) are shown as orange points in Figure 1.

Following the same procedures described in Corsaro et al. (2021), we performed linear and quadratic fits to both the combined sample and the MWO sample by itself. The Bayesian evidence strongly supports the quadratic model in both cases, indicating a small departure from linearity across the observed color range. The fit relation (dashed line in Figure 1) has the same form as Eq.(11) in Corsaro et al. (2021), $\tau_c = b'_1 + b'_2(\mathrm{G_{BP}-G_{RP}}) + b'_3(\mathrm{G_{BP}-G_{RP}})^2$ days, with the following parameters: $b'_1 = -106.6^{+4.6}_{-4.5}$ d, $b'_2 = 204.4^{+10.9}_{-11.3}$ d mag$^{-1}$, and $b'_3 = -26.1^{+6.6}_{-6.4}$ d mag$^{-2}$. The shaded region in Figure 1 indicates the $1\sigma$ credible interval, and the linear fit is shown as a dotted line for comparison.

## 4. DISCUSSION

There is remarkable agreement between the asteroseismically calibrated values of $\tau_c$ and those inferred from the measured mean activity levels and rotation periods (only the same zero-point is enforced by our choice of $\mathrm{Ro}_\odot$). This validates our assumption that $\langle R'_{\rm HK}\rangle \propto \mathrm{Ro}^{-1}$. Our quadratic fit to the combined sample is nearly linear between $0.55 < \mathrm{G_{BP}-G_{RP}} < 1.2$, and can be used to estimate Ro for stars with spectral types between F5 and K3. Notably, the asteroseismic sample appears to be confined to the lowest values of $\tau_c$ at the reddest colors. These targets generally have higher Rossby numbers and lower activity levels, where the weaker intrinsic oscillation amplitudes are least suppressed by magnetic activity. Consequently, the strong deviation from linearity in the original asteroseismic calibration may reflect an observational bias against the detection of solar-like oscillations at higher activity levels for the coolest stars.

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