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Exploration of CDPP in 20s TESS Data*

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ABSTRACT

The introduction of TESS's 20 second cadence mode has given us the opportunity to examine the variation of stellar flux on shorter time scales than ever before. Characterizing this variation for different spectral types has utility in many fields such as variable stars, exoplanets, and observation planning. One metric used to quantify stellar variation, the combined differential photometric precision (CDPP), is of particular interest in exoplanet searches. The 20 second cadence data allowed us to estimate CDPP values on the short timescales required for mapping transit ingress and egress, looking for atmospheric asymmetries, and so forth. In our exploration of CDPP we developed a pipeline to create light curves for our catalog of 57 stars. We reproduced the scaling seen between CDPP and magnitude at all timescales in our data set. We explored the CDPP at different timescales as well as examined trends with stellar parameters such as metallicity and temperature. Finally, we examined different CDPP calculation methods, along with the scaling detailed in (Christiansen et al. 2012).

Keywords: Variable Stars — Stellar Types — Exoplanets — CDPP — Asteroseismology — TESS

1. DATA SET

For our analysis, we have selected a sample of stars observed by the APOGEE (Holtzman et al. 2018) spectroscopic survey because of their location in the TESS Southern Continuous Viewing Zone. We chose 57 stars at particular temperatures and gravities that represent 19 interesting points of evolution, including a range of masses along the main sequence, subgiants, several points along the red giant branch, the primary and secondary red clump, and the asymptotic giant branch phase. For each evolutionary point, we have 12-13 sectors of TESS cycle 3 observations for the three brightest stars with spectra, in order to provide redundancy that will allow us to distinguish astrophysical signals from spacecraft noise introduced into the light curve of any individual star or sector.

TESS's SPOC pipeline provides light curves generated via Simple Aperture Photometry (SAP) and Presearch Data Conditioning SAP (Jenkins et al. 2016). However, this pipeline produces light curves that retain significant instrument systematics caused by spacecraft operation and scattered light. Additionally, our star sample was observed over at least 12 sectors, and these systematics are sector dependent (Avallone et al. 2022). Therefore we implemented a pipeline that cleans, normalizes, and stitches the sectors of each target into a single light curve.

The sample was checked for bad targets in the TESS multi sector Data Release Notes (Fausnaugh et al. 2021). Additionally, the TPF files for each target were checked for crowding using methods described in (Barclay et al. 2020). We found crowding in three RGB targets, and removed them from our data set.

For all targets, we start by removing NaN values, sigma clipping outliers greater than 5σ, and removing data points with a non zero quality flag from all sectors. We clip the first and last days of each sector, as well as one day regions around TESS safe modes and discontinuities, as this is where scattered light and systematic effects are most prevalent (Avallone et al. 2022). The sectors are median-normalized, then stitched together into a single light curve for the given target. We compare our light curves to those made by other published papers (Nandakumar et al. 2022) and find generally consistent results.

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2. CDPP METHODS

The Combined Differential Photometric Precision was developed for the Kepler mission to determine the photometric noise in light curves (Christiansen et al. 2012). Photometric noise is non-uniform and non-stationary, and thus a photometric noise time series is generated by the Transiting Planet Search (TPS) module in the official Kepler pipeline for each target (Jenkins et al. 2016). CDPP is the root mean square of this time series on timescales relevant to transiting planets (generally 3, 6, and 12 hours). It is effectively the ease with which planet transit signatures can be detected in a given target (Christiansen et al. 2012), and is therefore a useful characterization of photometric noise for that target.

The official TPS module uses a wavelet-based algorithm to determine the signal-to-noise ratio for a specific transit time. However, there is a "sgCDPP proxy algorithm" that can be used to estimate CDPP, as discussed in Gilliland et al. (2011) and Cleve et al. (2016). `lightkurve`'s implementation of this method (adapted from the Matlab version used by Jeff Van Cleve) first removes low frequency signals using a Savitzky-Golay filter, σ clips the data, then computes the standard deviation of a running mean with a window length equal to the desired transit duration (Lightkurve Collaboration et al. 2018).

2.1. *Lightkurve's CDPP Proxy Algorithm*

We first estimated CDPP using the built in proxy algorithm in `lightkurve`. Initially there were issues with the σ clipping function that appeared after the `astropy 5.0` update. Specifically, the breakage would occur when `lightkurve`'s σ clipping method was used on a pre-made light curve object that had been flattened by their implementation of `scipy`'s Savitzky-Golay filter. However, this issue only appears in pre-made light curve objects, if a light curve is created from a target pixel file (TPF), the function works as intended. The issue was fixed by removing `astropy` units from within the σ clipping function, and adding them back at the end of the calculation. While this has been shown to generate values consistent with estimations done using light curve objects made from a TPF, it is not considered a permanent solution. We are currently working with the `lightkurve` team to resolve this issue.

A comparison of values calculated with this proxy method to values from the official Kepler pipeline was then done. Calculating the 1-hour CDPP and plotting against Gaia magnitude (Figure 1), we reproduce the overall trend found in the TESS data release notes, with CDPP increasing with magnitude. However, there is a noticeable discrepancy between the `lightkurve` estimation and the official Kepler method for some targets. It is still unclear why. In our sample, there are no obvious trends or links between these stars.

2.2. *Scaling CDPP*

It is shown in Christiansen et al. (2012) that we can estimate the effective CDPP ($CDPP_{eff}$) for a desired transit time (t_{dur}) by using the CDPP value calculated in the official pipeline and scaling it with:

$$CDPP_{eff} = \sqrt{t_{CDPP}/t_{dur}} \times CDPP_N \tag{1}$$

Where t_{CDPP} is the transit time from the official pipeline closest to t_{dur}, and $CDPP_N$ is the official CDPP value corresponding to that transit time (Christiansen et al. 2012). For TESS targets, CDPP is calculated by the TPS pipeline for 30-min, 1, and 2-hour transit times. For our examination of scaling, we calculate $CDPP_{eff}$ for transit times from 1 minute to 1-hour, on a minute to minute basis. We use the official 30-min CDPP, and scale it for t_{dur} of 1 to 45 minutes. For t_{dur} of 46 minutes to 1 hour, we scale the 1-hour CDPP value from the TPS pipeline.

In figure 2, we see similar values between the effective CDPP and estimated CDPP from the `lightkurve` algorithm for TIC 300809119, a solar like target. Both methods generate a negative exponential plot, and are generally consistent with one another. There is often a "bump" in the scaled value at the 45-minute mark. This is due to the change from using the 30-min to 1-hour $CDPP_N$ value. Thus, the scaling is usually not perfectly smooth.

3. MAGNITUDE CORRECTIONS

To look for trends in CDPP with other stellar parameters, we first correct for the magnitude. Following Kunimoto et al. (2022), we a fit a curve with three components,

$$\sigma = a + b \times 10^{0.2(G-10)} + c \times 10^{0.4(G-10)} \tag{2}$$

where G is the Gaia magnitude. We use `Scipy`'s curve fitting to determine the component values for our sample, giving $a = 94$, $b = 59$, and $c = 30$. The median 1-hour CDPP value of all available sectors for each target is used. After

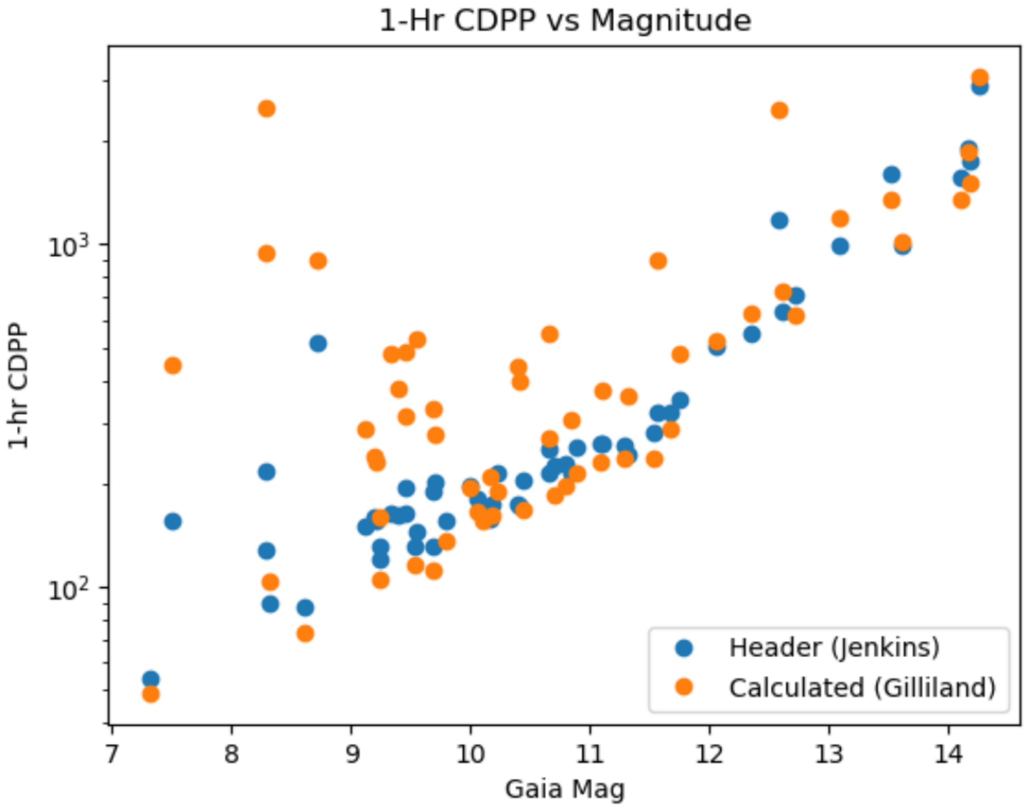

Figure 1. Comparison of 1-Hr CDPP values estimated by lightkurve and from TPS pipeline. Plotted against Gaia magnitude.

correcting for magnitude, we have three noticeable outliers with $CDPP\ Values > 2\sigma$. Two of which are much fainter than the rest of the sample so it could be due to noise, contamination from the instrument, or the data reduction. It is hard to be certain whether this deviation is meaningful. The third outlier, TIC 349902873, a potential SPB candidate, is interesting but we leave it to its own discussion in another paper.

NOTE: Add plot of the magnitude and cdpp before and after correction as well as before and after outlier removal.

4. RESULTS

5. CONCLUSIONS

6. ACKNOWLEDGEMENTS

This research made use of Lightkurve, a Python package for Kepler and TESS data analysis (Lightkurve Collaboration, 2018).

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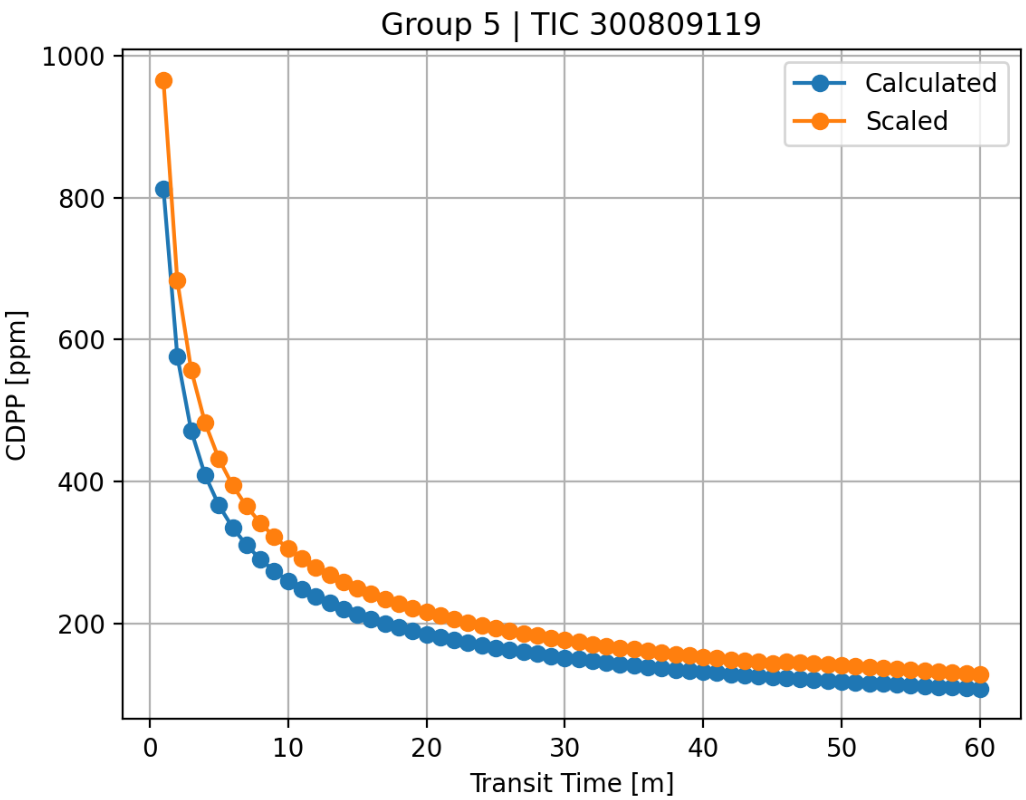

Figure 2. Comparison of 1-Hr CDPP values estimated by lightkurve and the effective CDPP scaled from TPS pipeline values via methods shown in Christiansen et al. (2012).

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