An Unprecedented Asteroseismic Data Set for the Oscillating Massive Star Spica

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Spica (Alpha Vir)

Spica is an eccentric double-lined spectroscopic massive binary system (P = 4.0145 d) which shows ellipsoidal variability, and whose more-evolved primary is an oscillating β Cep star with a primary radial oscillation period of approximately 5.75 d^{-1}. As one of the brightest stars in the sky (V = 0.97), Spica is an ideal laboratory for the study of the structure and evolution of massive stars.

We have collected 14 years of space-based high-precision photometry on Spica from WIRE (2005), MOST (2007), and K2 (Campaign 6 in 2015 and Campaign 17 in 2018), which spans a total of 194 days.

Data Reduction

Our analysis is based on four separate data sets, gathered using three different space-based photometry missions over a period of nearly 15 years.

- After its initial mission failure, the WIRE spacecraft operated as a photometric mission using its 50 mm star tracker (Buzasi 2001, 2004) from 1999 through 2007. Data shown here were gathered in 2005 and rereduced for this work. Most WIRE data were taken at a cadence of 0.5 *s* and binned to 15 *s* bins for increased ease of analysis, as is the case here.
- In 2007, the MOST spacecraft (Walker et al. 2003) observed Spica using its 150 mm aperture. These data have been previously published by Tkachenko et at. (2016) as part of a simultaneous analysis with time-resolved high-resolution spectroscopy.
- The K2 mission observed Spica twice, first in 2015 during Campaign 6 and then in 2018 during Campaign 17. Spica is a saturated target for Kepler/K2, and these data were reduced using the halo photometry technique developed by White et al. (2017; see Figure 1).

Figure 2 (top right) shows the light curves for each data set on the same scale, with the central time of the observation subtracted. Different data sets are color-coded for clarity. The K2 Campaign 6 is both the longest and highest-quality data set; Campaign 17 is both shorter and imperfectly extracted by the halo technique early on. The WIRE data have SNR comparable to Kepler, but the time series is shorter, while the MOST data are of somewhat poorer quality (though still far superior to ground-based photometry!).

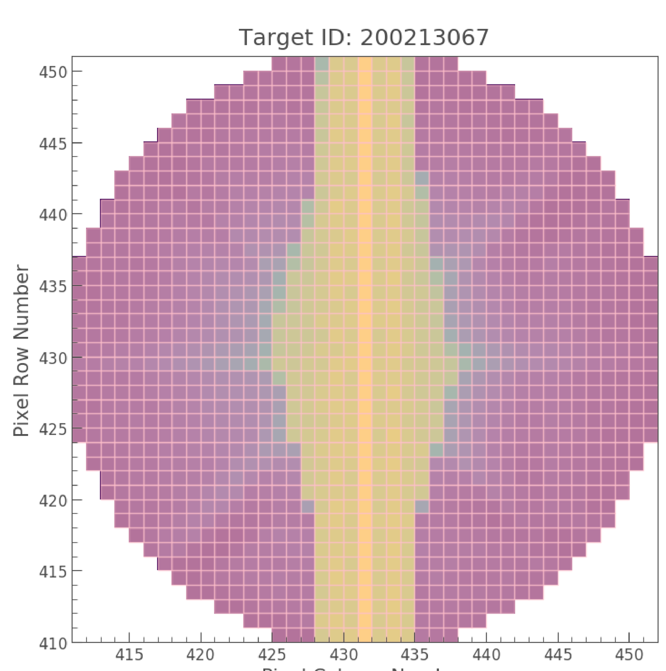

Fig. 1: The pixel weight map used for the halo photometry extraction for K2 C6.

Time Series Analysis

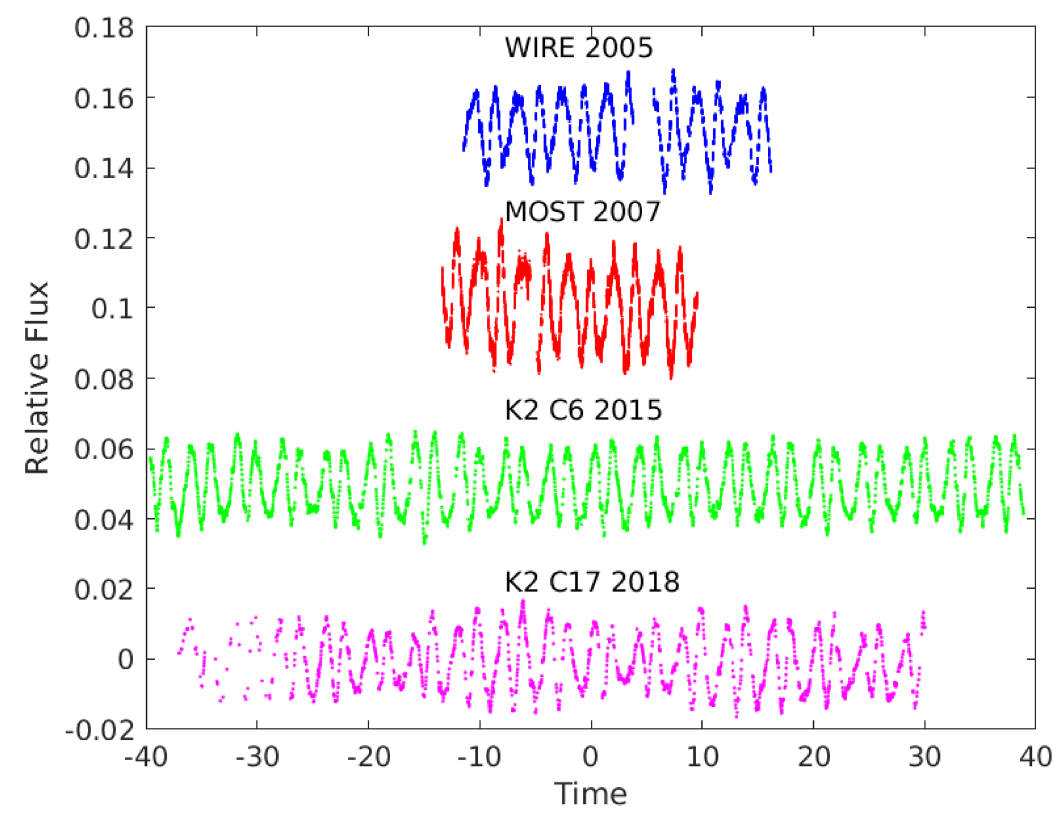

Fig. 2: Light curves for all four observation sets, in time order from top to bottom. Each is zero-centered to make the relative lengths of the time series obvious.

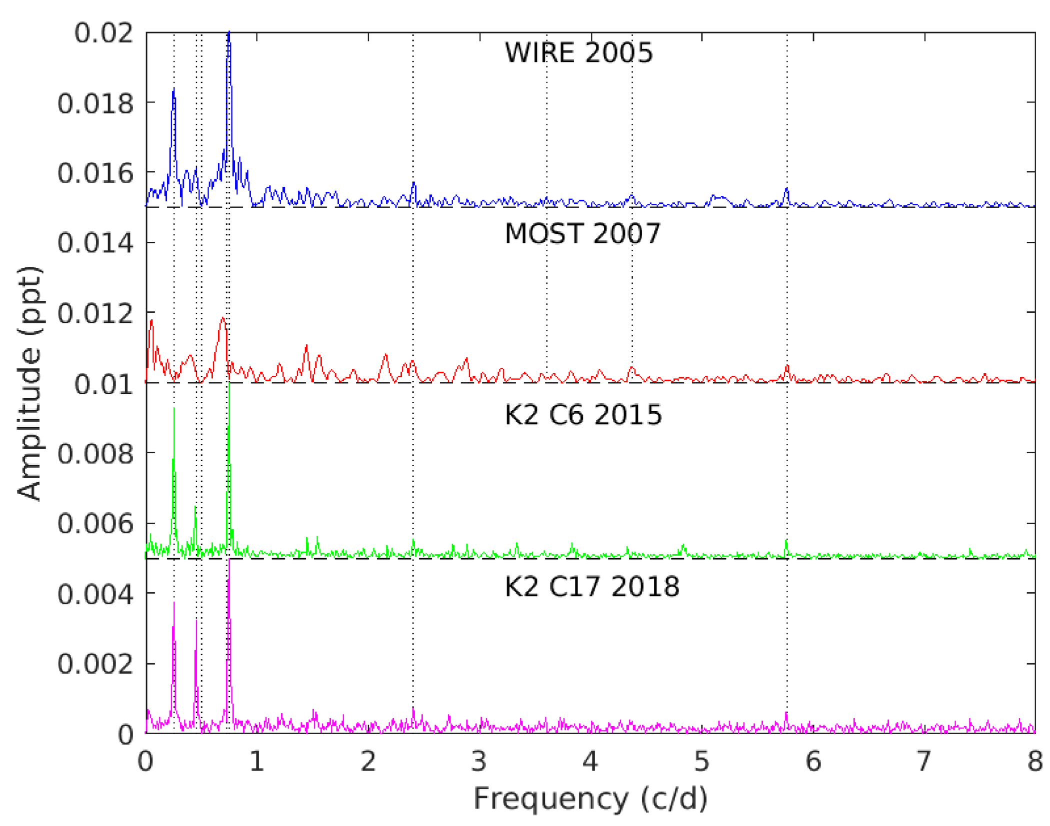

Fig. 3: Amplitude spectra for the time series shown above. The rotational frequency component has been prewhitened, and the vertical dashed lines illustrate the locations of the frequencies shown in the Table below.

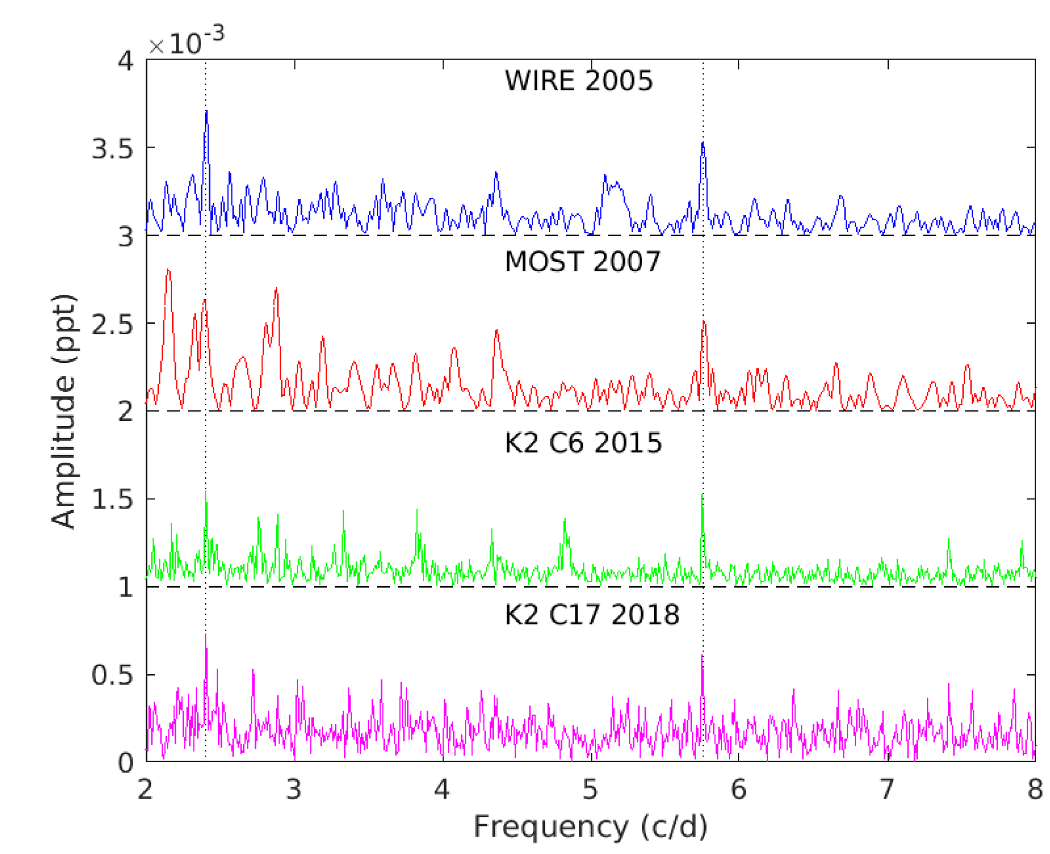

Fig. 4: The upper frequency range of Figure 3. Note the expanded vertical scale.

MOST	WIRE	K2 C6	K2 C17	Notes
0.249	0.248	0.249	0.249	f_{rot}
-	0.498	0.498	0.499	$2f_{rot}$
0.762	0.748	0.748	0.747	$3f_{rot}$
-	-	0.727	0.731	
-	0.448	0.442	0.452	
-	2.402	2.405	2.403	
5.764	5.764	5.754	5.755	
4.469	4.371	-	-	
3.553	3.606	-	-	

Table 1: Observed Frequencies (in c d^{-1}) for each light curve. The analysis is still preliminary and only those frequencies with SNR $>$ 4 are shown.

Data Analysis

We approached frequency analysis in two ways, to improve confidence in our results. In 3 cases the first and largest peak identified was consistently that corresponding to the rotation period. However, for the MOST data set the first alias peak was instead identified by both approaches; in those cases we forced identification of the first frequency identified with the (known) rotation period.

- We used Period04 (Lenz & Breger 2005) to identify frequencies down to a limit of $SNR = 4$ for individual peaks. Period04 uses a DFT followed by individual sine curve fits to improve frequency and amplitude fits. The individual fits were then removed from the time series and the resulting residuals searched for further periodicities, until the underlying noise level of the data is reached.
- In addition, we used a code one of us (DLB) developed for use with TESS data (see, e.g., Pedersen et al. 2019), which makes use of a DFT to find initial peaks. Each peak location is then improved with an oversampled DFT, and a spline fit to the data phased at that frequency is then removed from the data. As above, we only accepted peaks with a local $SNR > 4$

Figure 3 (middle left) shows the amplitude spectra from the second method for all four data sets, offset for improved clarity. Vertical dashed lines correspond to the frequencies identified in Table 1 (bottom left), while Figure 4 shows an expanded amplitude spectrum of the higher frequency range for the data sets.

Discussion

Within the errors ($\delta\nu < 0.001$ c d^{-1}) the frequencies of all common lines appear to be identical. However, a few frequencies visible in the K2 and WIRE do not appear in MOST, though this may be due to the somewhat poorer quality of the MOST data; a similar explanation may apply to the absence of the 0.73 c d^{-1} peak in the WIRE data. Most interesting, though, are the two peaks at $\sim$ 4.4 and $\sim$ 3.6 c d^{-1}, which are visible in both WIRE and MOST but not in K2, and may represent secular changes in the Spica system. We note that these peaks are not orbital aliases in WIRE and MOST, because there are substantial differences between the orbital periods of the two satellites. They are, however, fairly close to the well-known $\sim$ 6 hr periodicity in K2 time series and thus may have been inadvertently removed by detrending; we are conducting numerical experiments to address this possibility.

References

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