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WASP-4 IS ACCELERATING TOWARDS THE EARTH

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We recently showed that under the assumption of a constant orbital period, the hot Jupiter WASP-4b transited ≈82 seconds early for the TESS spacecraft (Bouma et al. 2019). Our timing analysis included data from peer-reviewed literature for which the times were measured from a single transit, and for which the midpoint was allowed to be a free parameter. We also required the time system to be clearly documented. In other words, we needed to know whether any heliocentric or barycentric corrections had been performed, and whether the absolute time system was UTC or TDB. The transit times we analyzed spanned 2007 to 2019 (Wilson et al. 2008; Gillon et al. 2009; Winn et al. 2009; Dragomir et al. 2011; Sanchis-Ojeda et al. 2011; Nikolov et al. 2012; Hoyer et al. 2013; Ranjan et al. 2014; Huitson et al. 2017). The combined timing data were best fit by an ephemeris with a constant negative period derivative; our best-fit decay rate was $\dot{P} = -12.6 \pm 1.2$ milliseconds per year. Our interpretation was that the apparent period change could be caused by any of three scenarios: a decaying orbit, a precessing orbit, and an orbit being gravitationally perturbed by an outer companion.

Thereafter, Southworth et al. (2019) reported 22 new transit times for the system, and confirmed that the updated series of transit times was consistent with a quadratic ephemeris. Their interpretation of the timing variations did not differ in any major respects from our own, though with additional data they found a lower best-fit decay rate of $\dot{P} = -XX.X \pm X.X$ milliseconds per year.

A separate study by Baluev et al. (2019) reported additional light curves. Baluev et al. analyzed their newly obtained photometry, along with archival light curves that we omitted from our analysis due to systematic uncertainties in the absolute time system. Baluev et al. found that when they used all the available TTV data, the need for a quadratic ephemeris was present "at the high $\sim 5-7$ sigma level". However, they pointed out that if they used lower-precision subsets of the available timing data, the necessity for the quadratic term decreased. Baluev et al. also pointed out that the precise transit times reported by Huitson et al. (2017) were quite important in the time-series. Overall, Baluev et al. did not find the claim of a period decrease convincing.

One line of follow-up needed to confirm and understand the timing variation was additional radial velocity observations. The longest RV baseline previously available was six observations acquired by Knutson et al. (2014) and the CKS team on Keck HIRES from 2010 to 2013. This past season we acquired four additional observations with Keck HIRES. Even before fitting out the hot Jupiter, the residuals showed a strong linear trend.

For completeness, in our analysis we included CORALIE measurements from Wilson et al. (2008) and Triaud et al. (2010), using the homogeneous velocities reported by the latter authors. We included the HARPS values reported by Pont et al. (2011), which are identical to those from Husnoo et al. (2012). We omitted the HARPS data points taken over three nights by Triaud et al. (2010) for Rossiter-McLaughlin observations because they were calculated using a different pipeline than the longer-baseline Pont et al. measurements, and necessarily inclusion of an extra offset term would nullify their statistical value.

We then fitted a single Keplerian orbit, plus instrument offsets, jitters, and a linear trend (Fulton et al. 2018, `radvel`). We set Gaussian priors on the period and time of inferior conjunction using the values from Bouma et al. (2019), and fixed the eccentricity to zero, consistent with results from Beerer et al. (2011), Knutson et al. (2014) and Bonomo et al. (2017). The

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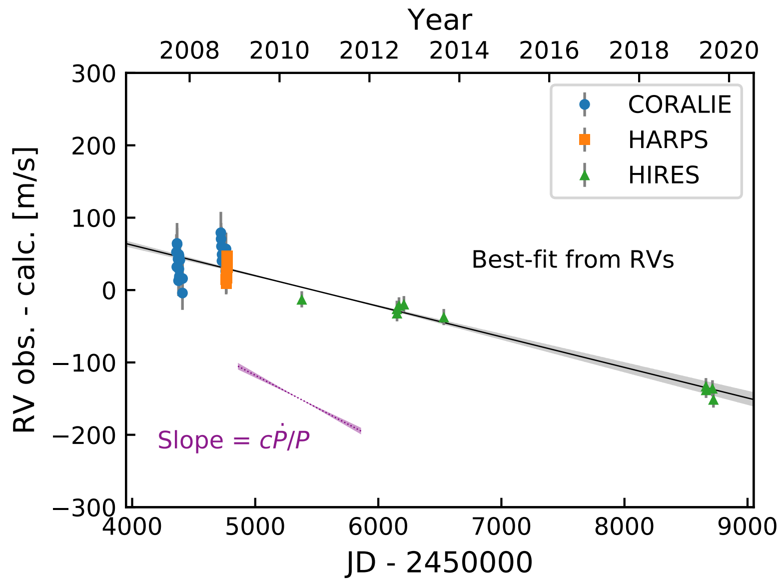

Figure 1. Radial velocity observations of WASP-4. The orbit of WASP-4b has been subtracted. The best-fit linear trend from the RVs is shown with the black line, with 1σ errors in gray. The trend needed to produce the period decrease of 12.6 milliseconds per year seen by Bouma et al. (2019) in transits is the purple dotted line in the bottom left.

remaining free parameters were the velocity semi-amplitude, the instrument zero-points, the instrument jitters (an additive white noise term for each instrument), and optionally a linear acceleration term ($\dot{v_r}$).

The AIC and BIC strongly favored a model with a linear trend (ΔBIC = 73 compared to a model without the linear trend). Figure 1 shows the best-fitting model, with the orbit of WASP-4b subtracted. The best-fit radial velocity derivative, $\dot{v_r}$, is

$$\dot{v_r} = -0.0422^{+0.0028}_{-0.0027}\,\mathrm{m\,s^{-1}\,day^{-1}}. \tag{1}$$

This acceleration towards our line of sight is 4.3 times faster than the $\approx 2\sigma$ trend Knutson et al. (2014) found from the shorter baseline. The radial velocity values are available in the data-behind-the-figure online version of this *Note*.

Under the assumption of constant acceleration, $\dot{P} = \dot{v_r}P/c$, the implied period decrease that should be seen in transits is roughly 5.9 ± 0.4 milliseconds per year. All the available TTV data show a period decrease of $\approx 8-12$ milliseconds per year (Bouma et al. 2019; Southworth et al. 2019; Baluev et al. 2019).

Though the quantitative agreement is not perfect, Occam's razor would suggest that the line of sight acceleration is probably a sufficient explanation for the apparent decrease of WASP-4b's orbital period. While further radial velocity observations of the system should help in determining the mass and semi-major axis of the companion, it seems unlikely that additional transit observations will yield near-term constraints on orbital decay.

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Software: `radvel` (Fulton et al. 2018)

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