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Yeehaw: A Roundup of Probabilistic Transit Modeling Packages

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The method of transit photometry has proven indispensable in the detection and characterization of thousands of exoplanets over the past few decades (Charbonneau et al. 2007; Winn 2009, 2010; Haswell 2010). Transits are particularly useful for determining relative radii (Heller 2019), constraining orbital inclination (Seager & Mallén-Ornelas 2003), and the planet's orbital ephemeris. These quantities all have to be inferred using a computed model of the planetary transit. Model accuracy directly affects the inference of these parameters and a recent study by Agol et al. (2020) has improved numerical accuracy of the popular quadratic limb-darkening law (Mandel & Agol 2002) to within $\mathcal{O}(10^{-15})$ along with analytical derivatives. This study directly probes the speed and accuracy of various limb-darkening laws, and we seek to improve upon that work and study how different models affect the statistical inference of transit parameters.

The following packages which provided limb-darkened transit curves were tested: `exoplanet` (Foreman-Mackey 2019), `BATMAN` (Kreidberg 2015), `PyTransit` (Parviainen 2015), and `EXOFASTv2` (Eastman et al. 2019). These libraries have a variety of limb-darkening laws, but all have a quadratic limb-darkening law following the framework of Mandel & Agol (2002). In addition, `exoplanet` and `EXOFASTv2` have entire statistical modeling frameworks built into or on top of the transit curves. We also test `Juliet` (Espinoza et al. 2019), which adds a statistical modeling framework to the `BATMAN` transit models.

To begin, we used the highly accurate Agol et al. (2020) transit models to simulate a light curve. We build a hierarchical model using the `exoplanet` framework with the following parameters: the semi-major axis, orbital period, time of inferior conjunction, ratio of planet to stellar radii, limb-darkening coefficients, and out-of-transit noise. The ground truth parameters were chosen to roughly mock the Kepler-101b transit (Bonomo et al. 2014) and are shown in Table 1.

Table 1. Posterior outputs from each statistical model experiment. The uncertainty bounds are given by the 68% highest-posterior density interval.

	P [d]	$t0$ [d]	R_p/R_*	aR_*	u_1	u_2	σ
ground truth	3.5	1.3	0.03	10	0.5	0.2	$1e-4$
exoplanet+NUTS	$3.5^{+5.66e-05}_{-5.81e-05}$	$1.3^{+0.000186}_{-0.000181}$	$0.0302^{+0.000119}_{-0.000104}$	$10.0^{+0.0301}_{-0.0299}$	$0.552^{+0.0567}_{-0.067}$	$0.0479^{+0.116}_{-0.101}$	$9.97e-05^{+6.15e-07}_{-5.52e-07}$
exoplanet+MH	$3.5^{+6.22e-05}_{-5.56e-05}$	$1.3^{+0.000182}_{-0.000193}$	$0.0302^{+0.000111}_{-0.00011}$	$10.0^{+0.0306}_{-0.0296}$	$0.552^{+0.0647}_{-0.0562}$	$0.048^{+0.103}_{-0.11}$	$9.97e-05^{+5.93e-07}_{-5.59e-07}$
BATMAN+MH	$3.5^{+6.32e-05}_{-5.28e-05}$	$1.3^{+0.000171}_{-0.000198}$	$0.0302^{+0.000106}_{-0.000118}$	$10.0^{+0.0337}_{-0.0275}$	$0.551^{+0.0568}_{-0.0694}$	$0.0523^{+0.118}_{-0.106}$	$9.97e-05^{+5.69e-07}_{-5.83e-07}$
PyTransit+MH	$3.5^{+5.95e-05}_{-5.45e-05}$	$1.3^{+0.000194}_{-0.000168}$	$0.0302^{+0.000115}_{-0.000109}$	$10.0^{+0.0336}_{-0.027}$	$0.555^{+0.0687}_{-0.0599}$	$0.0422^{+0.107}_{-0.116}$	$9.97e-05^{+5.95e-07}_{-5.64e-07}$
Juliet+NS	$3.5^{+5.83e-05}_{-5.67e-05}$	$1.3^{+0.000175}_{-0.000198}$	$0.0302^{+0.00011}_{-0.00011}$	$10.0^{+0.0273}_{-0.0325}$	$0.552^{+0.0632}_{-0.0572}$	$0.0476^{+0.104}_{-0.108}$	
EXOFASTv2+MH	$3.5^{+5.97e-05}_{-5.8e-05}$	$1.3^{+0.000173}_{-0.000196}$	$0.0302^{+0.000107}_{-9.79e-05}$	$10.0^{+0.0227}_{-0.0249}$	$0.405^{+0.0274}_{-0.0268}$	$0.28^{+0.0411}_{-0.0403}$	$9.98e-05^{+6.07e-07}_{-5.58e-07}$

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