Constraining the Densities of the Three Kepler-289 Planets with Transit Timing Variations

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Abstract

Kepler-289 is a three-planet system exhibiting Transit Timing Variations (TTVs). Kepler-289 contains two sub-Neptunes and one gas giant planet orbiting a young, Sun-like star whose light curve exhibits significant variability due to rotational modulation from starspots. All three planets orbit within 0.52 AU of the host star with orbital periods just below a 1:2:4 Laplace orbital resonance. We observe a transit of Kepler-289c with the WIRC instrument on the 200" Hale Telescope at Palomar Observatory, using diffuser-assisted photometry to achieve space-like photometric precision from the ground. This new transit observation extends the original four-year Kepler TTV baseline by an additional 6.5 years. We re-reduce the archival Kepler data with an improved stellar activity correction and carry out a joint fit with the Palomar data to constrain the transit shape and derive updated transit times. We then model the TTVs to determine the masses of the three planets and constrain their densities. Our new analysis results in improved mass and density estimates for all three planets, with the innermost planet showing the largest improvement.

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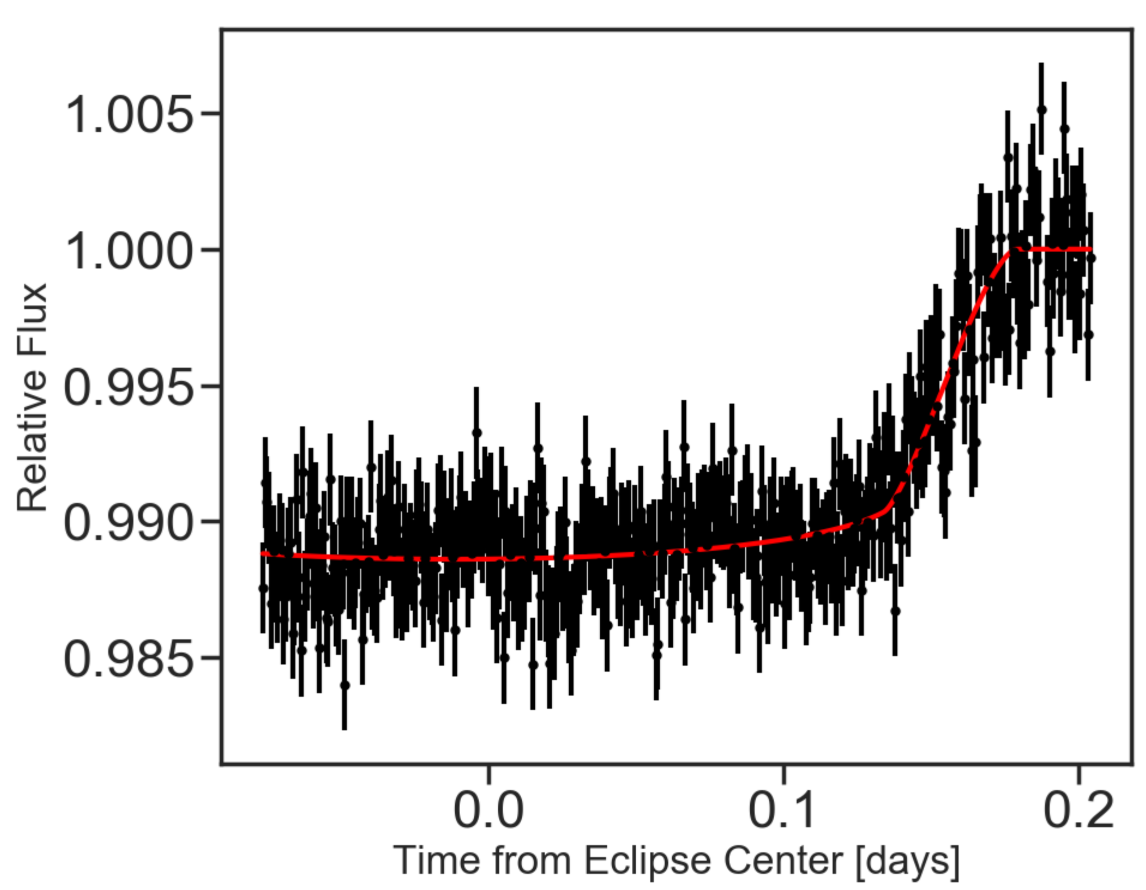
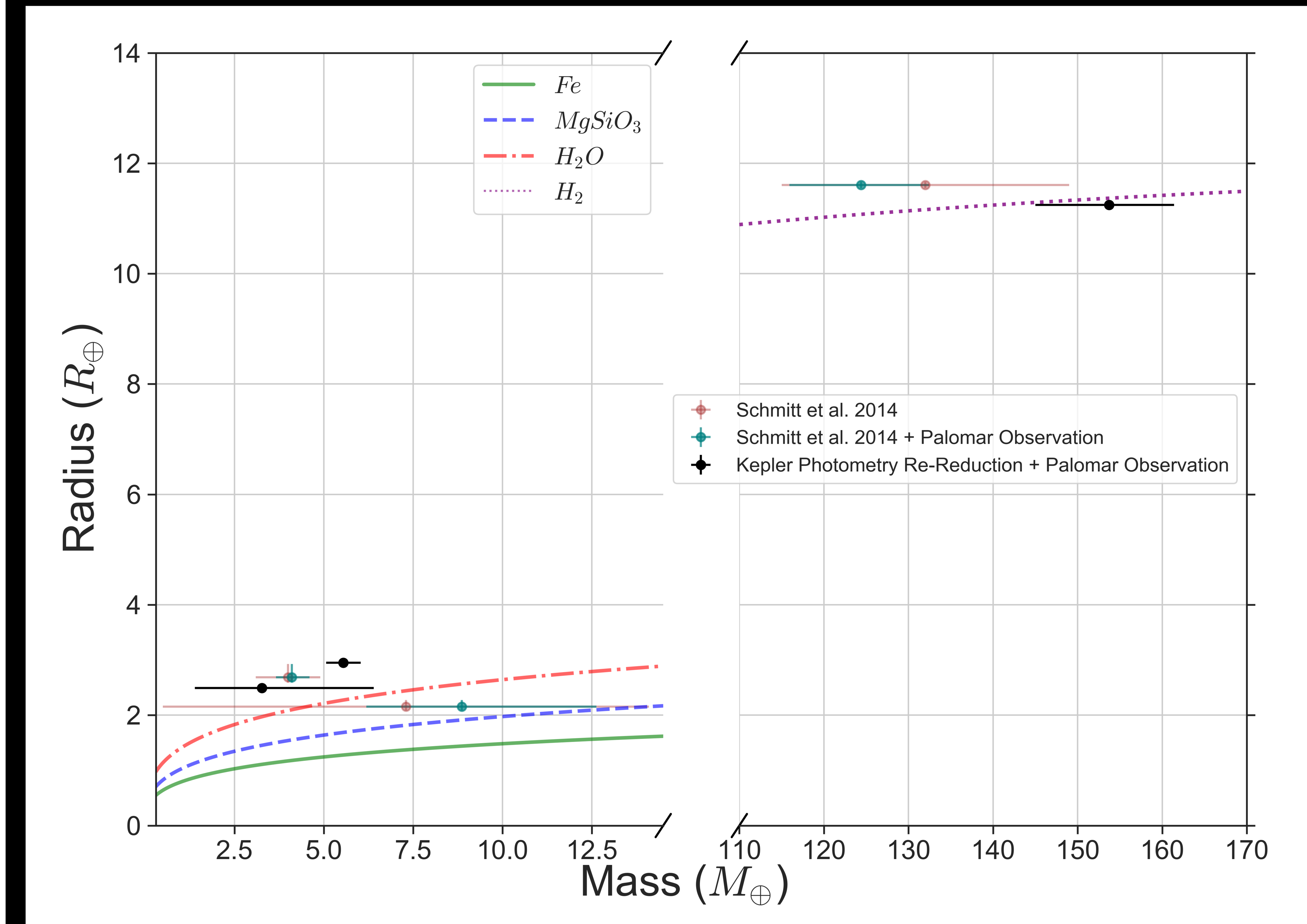
BACKGROUND: **Transit timing variations (TTVs) are a powerful tool that enables us to determine precise masses for planets. Kepler-289 is a young (0.6 Gyr), sun-like star, hosting three planets with orbital periods of 34.5, 66.1, and 125.9 days, and exhibiting TTVs [1]. The star is significantly variable (~3%) due to rotational modulation from starspots, making transit midtimes and thus TTV mass estimates difficult to constrain, especially for the innermost planet.**

METHODS: We re-reduced photometric data from the Kepler Space Telescope with special consideration for starspot modulation and crossings. We also observe a transit of Kepler289c with diffuser-assisted photometry [2] on the Hale Telescope at Palomar Observatory to extend the TTV baseline by more than 6 years. We recalculate the TTVs, and model those TTVs to determine new masses for the three planets.

The transit we observed from Palomar:

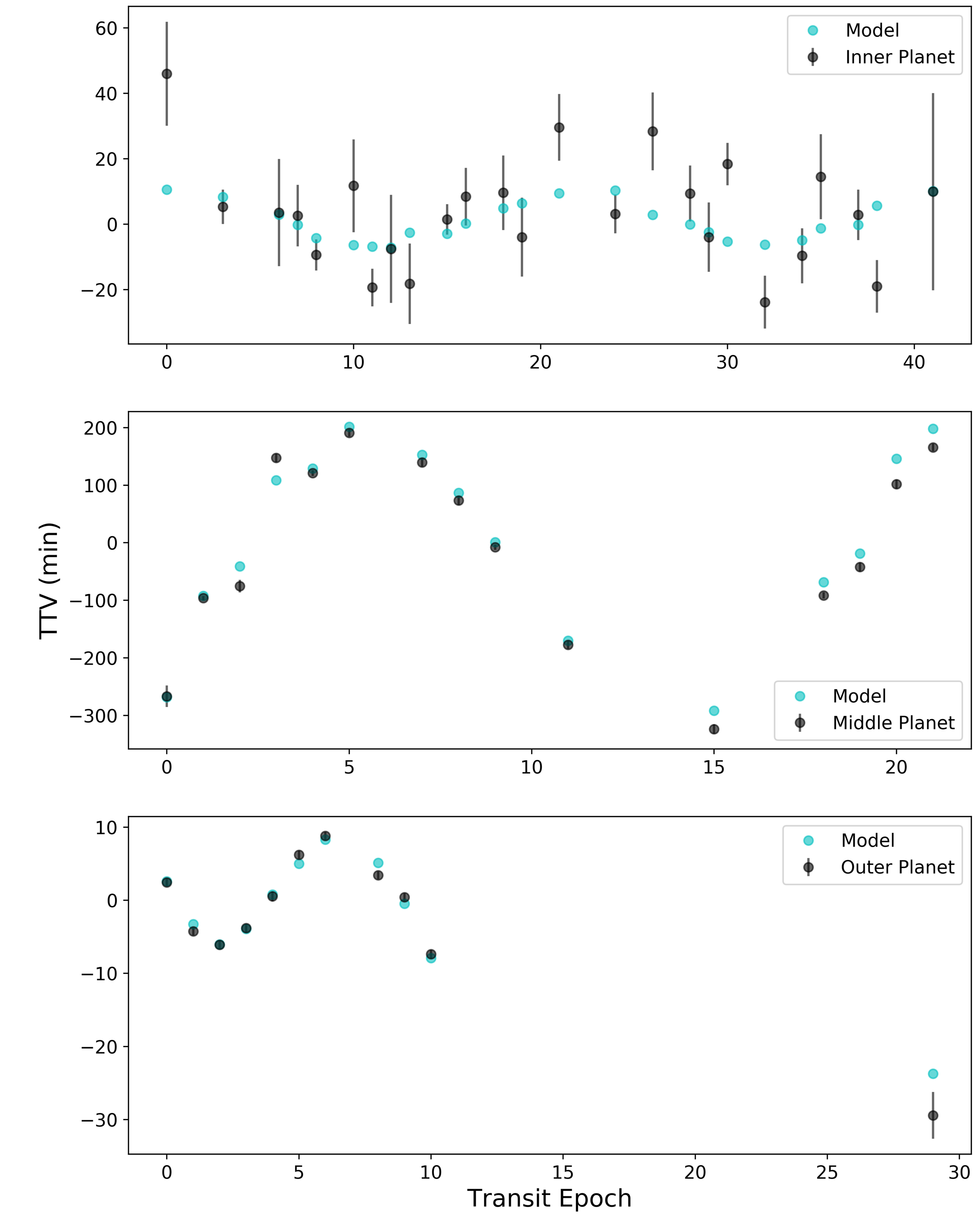


The young, sun-like star Kepler-289 hosts three planets orbiting near a 1:2:4 Laplace resonance: two super-Earths and one gas giant



Comparison of the three Kepler-289 planets in mass-radii space, including their original confirmation in 2014 [1], new decreased mass uncertainties after our Palomar observation, and further decreased mass and radii uncertainties after recalculating transit midtimes with our improved Kepler photometry. Constant composition curves for iron, silicate, and water ice planets are shown for reference from [3], and molecular hydrogen from [4] .

SUPPORTING EVIDENCE:
The observed TTVs for all three planets from the re-reduction of the Kepler photometry, along with best-fit results from our MCMC modeling with TTVFast [5] of the TTVs to determine the planet masses:



RESULTS: We reduce the mass uncertainties for all three Kepleer-289 planets by more than a factor of two. We determine new densities for the planets, which are 1.17 g/cc, 1.19 g/cc, and 0.60 g/cc for the inner, middle, and outer planets of Kepler-289b/c/d, respectively.

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