National Aeronautics and Space Administration

Four newborn planets transiting a young solar analog

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Program: Strategic Initiative

Project Objective:

Planet properties evolve with time, and this evolution is particularly dramatic for planets at small orbital separations close to their stars. Radii shrink and temperatures drop as gaseous planets cool and contract. Eccentric orbits circularize under the influence of stellar tidal potentials. Atmospheres may erode from exposure to intense stellar emission at X-ray and extreme UV wavelengths. Theoretical models predict that the radii of *Kepler*-type planets (periods < 100 days, radii < 4 $R_\oplus$) are several times larger at ages of a few to tens of million years (Owen & Wu 2013). While there is no shortage of theoretical predictions, there is a serious dearth of planets known around young stars. Consequently, each young exoplanet is a rare and valuable benchmark with which theoretical planet evolution models can be tested. **Our objective is to find and characterize young exoplanets so that the early evolution of planet properties can be discerned for the first time. Characterizing the youngest exoplanets can help us understand processes important early in our own solar system's history, and provide context for understanding the observed properties of mature exoplanetary systems.**

FY18/19 Results:

We presented the discovery of four large planets transiting V1298 Tau, a solar-mass star with an age of 23 ± 4 Myr. V1298 Tau is now established as one of the youngest known exoplanet hosts and the ***first case of a pre-main sequence star with multiple transiting planets***.

1. We find that the planets orbiting V1298 Tau are anomalously large (5.6-10.3 R_{Earth} ; Fig. 2), continuing a trend of large planets found around young stars. One interpretation is that the V1298 Tau planets are still undergoing radial contraction and emitting heat from their formation.

2. While the planet masses have not yet been determined, dynamical constraints suggest total masses of 2-28 M_{Earth} and 9-120 M_{Earth} for the two innermost planet pairs. This is some of the strongest evidence to date that some young exoplanets appear to be inflated.

3. Assuming plausible masses for the planets, and using an exoplanet mass-radius relation calibrated to evolved planets, suggests that the V1298 Tau planets may contract by as much as 40—90% over the coming evolution of the system.

4. The proximity of the V1298 Tau planets to orbital resonances (planets c & d are 0.25% outside of the nominal 3:2 mean-motion resonance, and planets d & b are 2.6% inside the 2:1) suggest that some planets may be born in resonance, or evolve into them on timescales shorter than or comparable to the age of the host star. One theory for forming resonant chains of close-in planets involves convergent migration of planets while still embedded in a viscous protoplanetary disk (e.g. Masset & Snellgrove 2001).

5. The V1298 Tau planetary system is a valuable laboratory for testing the theory of photo-evaporation, which suggests that the most common class of planet found by *Kepler* experiences substantial atmospheric loss early on when the planets are inflated and the stellar X-ray and UV emission is maximal.

Benefits to NASA and JPL (or significance of results):

The discovery and characterization of the planets orbiting V1298 Tau has implications for several of NASA's previous and planned missions. First, the V1298 Tau system sheds light on the origins of close-in multi-planet systems such as those found by the *Kepler, K2,* and *TESS* missions. Given the strong suggestion that the planets are inflated (and thus likely to have large atmospheric scale heights), V1298 Tau also represents a compelling target for atmospheric characterization via transit transmission spectroscopy with the *James Webb Space Telescope*. The atmosphere of a young, close-in exoplanet has never been characterized in detail and V1298 Tau presents one of the best opportunities to do so. Finally, if the temperatures and luminosities of the V1298 Tau planets can be measured through secondary eclipse spectroscopy, the system will have implications for the yields of planned missions or concepts with planet imaging components (such as *WFIRST, Origins, HabEx,* or *LUVOIR).*

The methods of detection and characterization we presented in the discovery papers (David et al. 2019a,b) represent the state-of-the-art for young and active stars. These methods can and will be applied to new data sets such as *TESS* light curves to maximize the impact of that mission and increase the sample of young exoplanets.

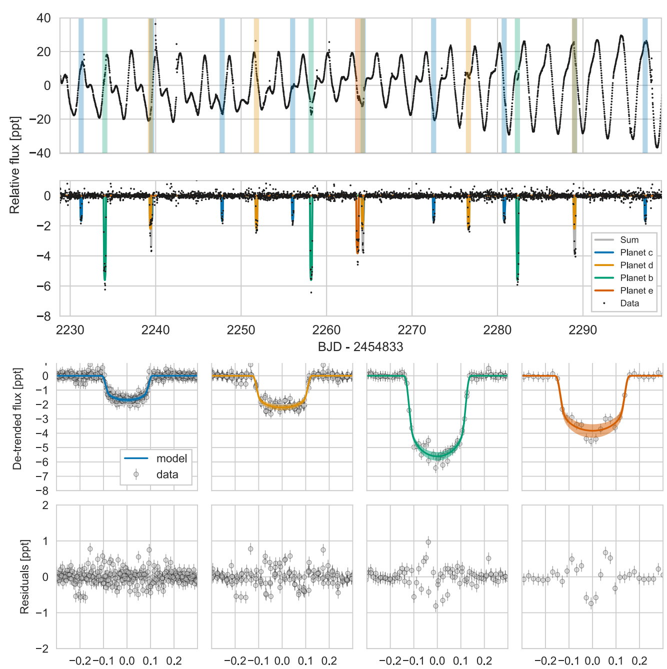

Figure 1. *K2 light curve of V1298 Tau before and after subtraction of the GP model (top two panels). Quasi-periodic brightness modulations with a period of 2.86 days are due to rotation of the star's spotted surface. Phase-folded transit data (points), mean transit models (solid lines) and their 1-σ contours (shaded bands) are shown in the third row. Below, residuals from the mean transit model.*

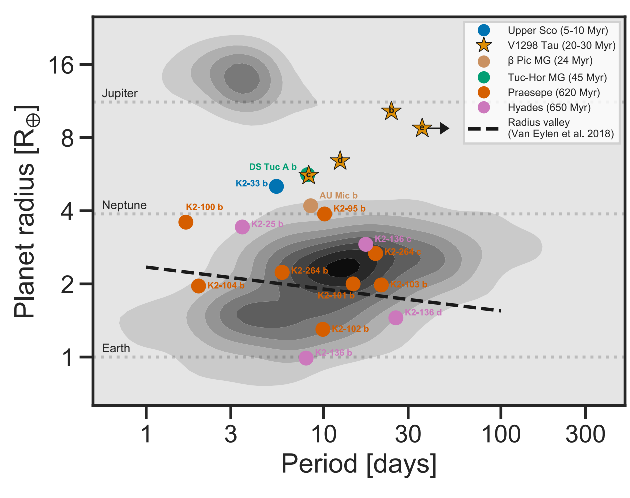

Figure 2. *Contours show a kernel density estimate of known transiting exoplanets in the orbital period vs. radius plane. Many of the youngest known planets reside in sparsely populated regions of this parameter space, hinting at ongoing evolutionary processes such as radial contraction, atmospheric erosion, and/or orbital migration.*

Publications:

1. T. J. David, A.M. Cody, C. L. Hedges, E. E. Mamajek, L.A. Hillenbrand, D.R. Ciardi, C.A. Beichman, E.A. Petigura, B.J. Fulton, H.T. Isaacson, A.W. Howard, J. Gagne, N.K. Saunders, L.M. Rebulla, J.R. Stauffer, G. Vasisht, S. Hinkley, 2019, "A Warm Jupiter-sized Planet Transiting the Pre-main Sequence Star V1298 Tau", *The Astronomical Journal,* 158, 79
2. T. J. David, A.M. Cody, C. L. Hedges, E. E. Mamajek, L.A. Hillenbrand, D.R. Ciardi, C.A. Beichman, E.A. Petigura, B.J. Fulton, H.T. Isaacson, A.W. Howard, J. Gagne, N.K. Saunders, L.M. Rebulla, J.R. Stauffer, G. Vasisht, S. Hinkley, 2019, "A Family of Newborn Planets Transiting a Young Solar Analog at 20-30 Myr", *Extreme Solar Systems 4*, id. 203.01, BAAS, Vol. 501, No. 6
3. T. J. David, E. A. Petigura, R. Luger, D. Foreman-Mackey, J.H. Livingston, E.E. Mamajek, L.A. Hillenbrand, 2019, "Four Newborn Planets Transiting the Young Solar Analog V1298 Tau", submitted to *AAS journals*

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