H-Alpha Variability of V1298 Tau c

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ABSTRACT
The 23 Myr system V1298 Tau hosts four transiting planets and is a valuable laboratory for exploring the early stages of planet evolution soon after formation of the star. We observe the innermost planet, V1298 Tau c, during transit using LBT PEPSI to obtain high spectral resolution characterization of escaping material near the H-α line. We find no strong evidence for atmospheric material escaping at the orbital velocity of the planet. Instead, we find a deep stellar feature that is variable on the few percent level, similar to a previous observation of the planet and can be explained by stellar activity. We attempted to monitor the broadband optical transit with LBT MODS but do not achieve the precision needed to characterize the atmosphere or improve the ephemeris.

INTRODUCTION
Statistical surveys of planet occurrence rates indicate that there is a radius gap between Earth-sized and sub-Neptune-sized planets (Fulton et al. 2017) that could arise from core-powered mass loss (Gupta & Schlichting 2019) and/or photoevaporation (Owen & Wu 2017). V1298 Tau is a young (23 Myr) bright system with 4 transiting planets (David et al. 2019b, a) that can reveal the evolutionary processes shaping the radius gap. We observe the V1298 Tau c planet to search for escaping Hydrogen and to constrain the atmospheric hazes or clouds with optical broadband spectroscopy.

OBSERVATIONS
We observed V1298 Tau c with the Large Binocular Telescope (LBT) on UT 2020-11-14 during primary transit under LBT program AZ-2020B-016. We used an ephemeris derived from Spitzer Data (John Livingston, private communication). The telescope was configured in heterogenous binocular mode where light from the DX 8.4 m primary fed the PEPSI instrument while light from the SX 8.4 primary fed the MODS-1 instrument.

The PEPSI instrument was configured to use the CD5 disperser on the red side to capture the 656 nm H-α line and the CD1 disperser on the blue side to capture the Ca II H and K lines at 393.3 and 396.8 nm, with a resolution of $R \approx 120,000$.

Standard pipeline processing of the PEPSI spectra was used with the numerical toolkit and graphical interface described in Strassmeier et al. (2018). Cosmic ray outliers above 5% from the continuum were removed from the 1D spectrum and were replaced by linear interpolation of neighboring points. We find that the Ca II H&K lines are seen in emission, but have too low signal-to-noise (SNR $\approx 7$) to adequately study variability near these lines.

RESULTS
We find an H-α profile that is similar to Feinstein et al. (2021). There is excess absorption at 55 km/s due to telluric contamination. The H-α line is variable, which we characterize with a velocity-integrated summation using the same velocity width as Feinstein et al. (2021): -64 to 91 km/s. We show the time series of the absorption in Figure 1, where...
the absorption decreases toward-mid-transit and increases after egress. Here, we plot the excess absorption, defined as

$$F_{\text{excess}} = \frac{F_{\text{mean}} - F(t)}{F_{\text{mean}}},$$

(1)

where $F(t)$ is the band-integrated flux from -64 to 91 km/s and $F_{\text{mean}}$ is the mean value of $F(t)$ for the out-of-transit measurements. We compare the variability to the projected orbital velocity of the planet as seen in the differential dynamic spectrum in Figure 1. For the orbital parameters, we use the inclination and semi-major axis from David et al. (2019a) and the Spitzer ephemeris. The H-\(\alpha\) variability does not follow the projected orbital velocity of the planet.

We note that the H-\(\alpha\) variability direction and magnitude is very similar to Feinstein et al. (2021). This could be due to similar chromospheric star spot and faculae geometry of the star at the two epochs. Given that the projected rotation velocity of the star is 23 km/s (David et al. 2019b), some of the H-\(\alpha\) variability could be related to faculae appearing in the line of sight as the star rotates. At an orbital phase near 0.013, there is excess flux at about -20 km/s that could be expected if faculae appear on the approaching limb of the star as it rotates.

Finally, we report that the MODS spectra did not give sufficient precision for characterization of the atmosphere. The MODS spectra were obtained in prism mode and were analyzed by both box extraction and multi-object spectroscopy but both methods led to large variability in the time series.

Continued monitoring of the system will provide insight about the atmospheres of the four known planets as well as the stellar variability. Narrowband photometry of the He line suggests that V1298 Tau d has an absorption signature while V1298 Tau c does not (Vissapragada et al. 2021).

**Figure 1.** The H-\(\alpha\) absorption line (left) is variable through the transit (middle). The fractional deviation from the mean of all out-of-transit spectra (right) shows that the absorption does not occur at the planet rest velocity (red dashed line) and is instead likely related to stellar activity. The absorption is also not confined to the transit which is between first and fourth contact (orange dotted lines).

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**Facilities:** LBT(PEPSI), LBT(MODS)

**Software:** astropy (Astropy Collaboration et al. 2013), photutils v0.3 (Bradley et al. 2016), ccdproc (Craig et al. 2015) matplotlib (Hunter 2007), numpy (van der Walt et al. 2011), scipy (Virtanen et al. 2020),
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