Validation of *Kepler* Planet Candidates Using Doppler Tomography

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Abstract

Kepler planet candidates around rapidly rotating stars are not amenable to follow-up using radial velocity observations, as these stars' broad spectral lines prevent precision radial velocity measurements. An alternative method of validating these candidates is to use Doppler tomography. This technique relies upon the Rossiter-McLaughlin effect, where the planetary disk transiting across a rotating star causes a perturbation in the stellar spectral line shape. In Doppler tomography, we spectroscopically resolve this line profile distortion. The detection of the movement of the line profile perturbation during the transit is an effective discriminant between bona fide planets and false positives involving eclipsing binaries. In addition, it provides information on the spin-orbit misalignment λ of the planet, a powerful statistical probe of planet migration. Doppler tomography is particularly suited to observations of planets around massive, rapidly rotating stars, currently a poorly explored region of parameter space. We present our detection of the transit of Kepler-13 Ab, as well as other recent results. We also highlight the potential of Doppler tomography for validating planet candidates from the upcoming TESS mission.

Doppler Tomography

For a rotating star, each surface element of the visible stellar disk will have a specific radial velocity, and thus will map to a specific region of the rotationally broadened stellar line profile. If there is a reduction of flux from this region—e.g., because it is obscured by a transiting planet—then there will be a lessened contribution to the stellar line profile at this velocity, resulting in a "bump" in the line profile. As the planet moves across the stellar disk, it will obscure regions of the stellar disk with different velocities, resulting in the movement of the line profile perturbation. This is typically displayed as a grayscale map of the time series line profiles residuals after the average line profile has been subtracted off; the transit signature manifests as a bright streak across the plot.

We now introduce a new method for binning the time series line profile residuals. This exploits the fact that, in the limit of solid body rotation of the host star, the transit signature will follow a straight line in velocity-time space. We can thus conduct a grid search over the physically allowed values of the slope of this line, and shift all of the time series line profile residuals in velocity space such that the transit signature will, if it lies along this line, occur at the same velocity. We then bin all of the line profiles residuals into a single high signal-to-noise line profile residual. If we have the correct slope, the transit signature in each individual line profile will line up and we will have a strong peak; if the slope is incorrect, the transit signatures from different line profiles will tend to average out, leaving only noise. This process is illustrated in Fig. 1 below for our data on Kepler-13 Ab.

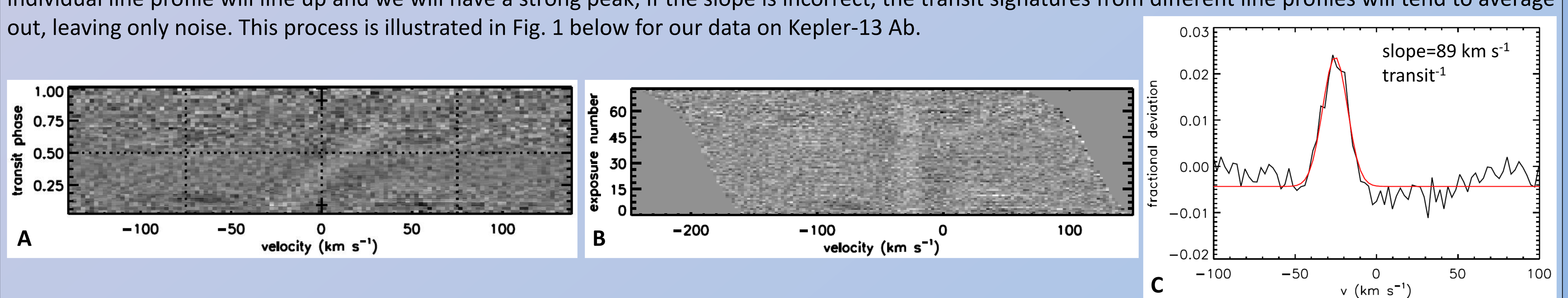

Fig. 1. A. Time series line profile residuals of Kepler-13 Ab. B. Time series line profile residuals shifted in velocity space such that the transit signature lies at the same velocity in every spectrum. C. Here we have binned the line profiles residuals in figure B, clearly displaying the peak caused by the transit signature; the x axis is the velocity at ingress. The slope is measured in units of the velocity span that the transit signature covers during the transit, i.e., km s^{-1} $transit^{-1}$.

Kepler-13 Ab: A Massive Hot Jupiter in a Multiple System with a Prograde, Misaligned Orbit

Kepler-13 (aka KOI-13, BD+46 2629) is a visual binary consisting of two similar A-type stars separated by ~1" (Szabó et al. 2011). A transiting planet candidate orbiting the brighter star was identified by *Kepler* (Borucki et al. 2011), and was confirmed through the detection of beaming and ellipsoidal variations by Shporer et al. (2011), Mazeh et al. (2012), Mislis & Hodgkin (2012), and Esteves et al. (2013). Using this method these authors measured the mass of the planet to be ~8-10 M_J. The spin-orbit misalignment of the planet was measured by Barnes et al. (2011), using the gravity-darkened lightcurve caused by the rapid rotation and consequent dynamical oblateness of Kepler-13A. They measured λ=±24°±4° or ±156°±4°; the degeneracy between prograde and retrograde orbits results from the fact that the stellar disk intensity profile is symmetric across the rotation axis.

We observed seven transits of Kepler-13 Ab with the 9.1m Hobby-Eberly Telescope (HET)/High Resolution Spectrograph (HRS) at McDonald Observatory. Analysis of the data is complicated by the fact that light from both Kepler-13 A and B enters the spectrograph, and that furthermore Kepler-13 B is itself a single-lined spectroscopic binary, possessing a low-mass stellar companion Kepler-13 C on a 66-day orbit (Santerne et al. 2012). This causes the Kepler-13 B line profile to move in velocity space relative to that of Kepler-13 A. Nevertheless, we have detected the transit of Kepler-13 Ab (Fig. 2). We measure λ=21.3°±0.2° and an impact parameter b=0.772±0.002; we note that the quoted formal errors are likely to be underestimates due to the relatively low signal-to-noise of our detection as well as systematic errors. A Markov chain Monte Carlo is under construction, and a preliminary version gives vsini=72.0 ± 1.5 km s^{-1}.

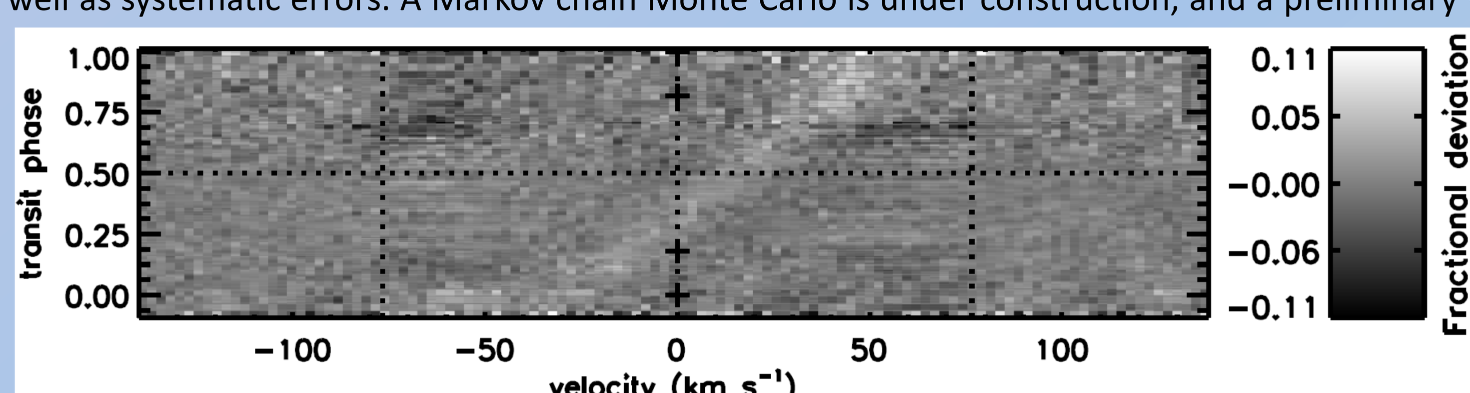

Fig. 2. Time series line profile residuals from seven transits of Kepler-13 Ab observed using the HET. The transit signature is the bright streak moving from bottom left to upper right. Time increases from bottom to top. Vertical dashed lines mark v=0 and v=±vsini, a horizontal dashed line marks the time of mid-transit, and small crosses mark the times of first, second, third, and fourth contacts.

Future Prospects

NASA's next planned exoplanet mission is the Transiting Exoplanet Survey Satellite (TESS). It will conduct an all-sky survey for transiting planets of super-Earth size and larger around bright (V<12) stars. Due to Malmquist bias, hot, luminous stars will have a greater representation among these stars than among the Kepler sample. TESS can thus discover many planet candidates that are amenable to validation and characterization via Doppler tomography. This will be greatly aided by the brighter target stars that TESS will observe. *Kepler* has found only a handful of planet candidates around hot stars, but TESS can provide the first statistically significant sample of planets around main sequence A stars, and Doppler tomography is a promising method for validating these candidates. We thus emphasize that TESS should include these stars in its sample.

Acknowledgments

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KOI-368.01: Tentative Detection of the Transit with a Prograde Orbit

KOI-368.01 is a transiting companion to an A star on an 110-day orbit. Zhou & Huang (2013) investigated this system using the Kepler lightcurve. They detected a secondary eclipse, showing that KOI-368.01 is a late M dwarf rather than a planetary companion. In addition, they modeled the shape of the gravity-darkened lightcurve for the transit, measuring a sky-projected spin-orbit misalignment of $\lambda=36°\,^{+23}_{-17}°$; like Barnes et al. (2011) there is a degeneracy between prograde and retrograde orbits, but Zhou & Huang (2013) assumed a prograde orbit for simplicity.

We observed one transit of KOI-368.01 on 2011 August 29 UT using the HET, plus an out-of-transit template observation on 2012 October 28 UT. While the transit signature is not evident in the time series line profile residuals (Fig. 3A), by binning the data as described elsewhere on this poster we do detect a peak suggestive of a transit signature (Fig. 3B). If this is indeed the transit signature, it shows that KOI-368.01 does orbit in the prograde direction. Our one transit observation only covers a small portion of the 13-hour-long transit, and so we have little leverage on the transit parameters, but our transit signature is consistent with the transit parameters measured by Zhou & Huang (2013).

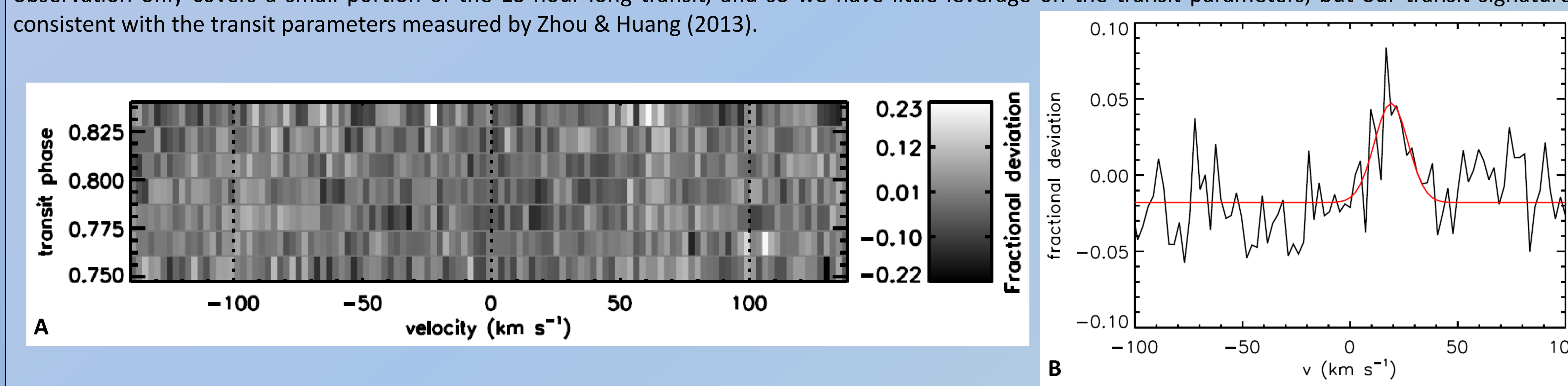

Fig. 3. A. Time series line profile residuals for one partial transit of KOI-368.01. B. Line profile residuals binned along a slope of Δv=64.7 km s^{-1} $transit^{-1}$, showing a Gaussian fit to the highest peak.

KOI-12.01: Tentative Detection of the Transit and a Curious Spectroscopic Transient

KOI-12.01 is a Kepler planet candidate on a 17-day orbit around a rapidly rotating (vsini=70 km s^{-1}) star. We observed three transits of KOI-12.01, on 2012 May 21 and 2013 April 25 and May 13 UT, using the HET. We have a preliminary detection of the transit signature (Fig. 4A), implying a prograde, low-inclination orbit; however, parallel dark streaks are also visible in the time series line profile residuals, challenging this interpretation.

The most prominent feature in our time series line profile residual maps, however, is a prominent but fading absorption feature at a velocity of +30 km s^{-1} relative to the systemic velocity of KOI-12, visible only in the data from 2013 April 25 (Fig. 4). A ~1.5-day period is evident in the *Kepler* lightcurve, likely from spot modulation; given this rotation period and the measured vsini of the star, this feature *cannot* be on the photosphere of KOI-12, as it would be expected to move by of order 10 km s^{-1} during the 1-hour HET observation. We cannot exclude that it could be due to a prominent, short-lived hot spot on KOI-12.01, if it is a stellar rather than planetary companion. This may be the case, as a 1.5-day rotational period for KOI-12 is incompatible with the vsini unless the stellar radius is ~2 R_{sun}, putting the radius of KOI-12.01 above that expected for a planetary companion on a 17-day orbit. The event fell during *Kepler*'s Q17, and once this lightcurve is publically released it may shed light on what is responsible for our line profile transient.

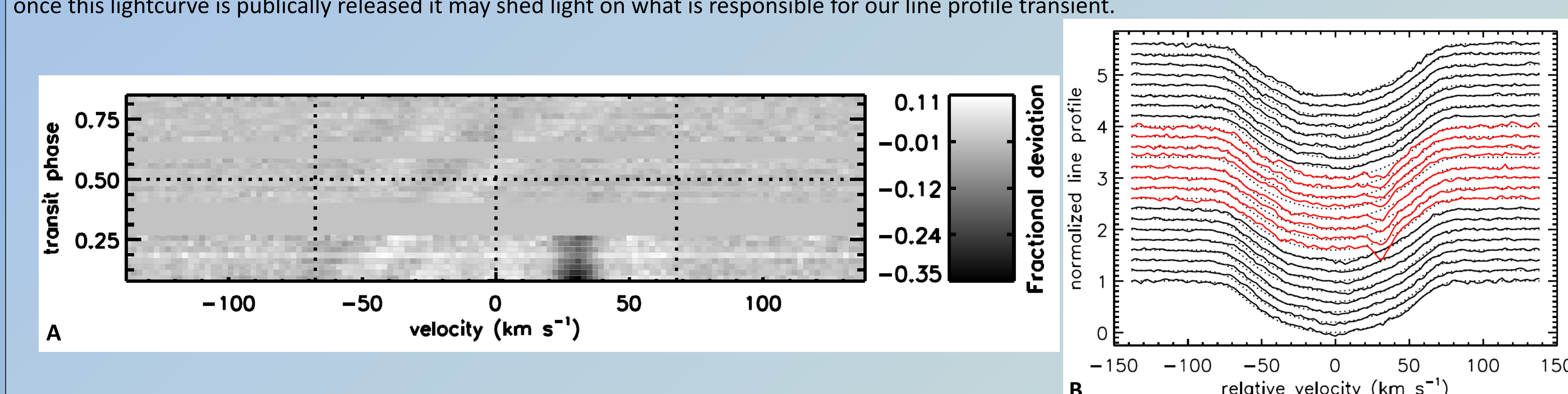

Fig. 4. A. Time series line profile residuals for three partial transits of KOI-12.01. The possible transit signature is the bright streak running from lower left to upper right. B. Time series line profiles for the three partial transits. Time increases from bottom to top, and each subsequent line profile is offset vertically by an arbitrary amount. The line profiles from 2013 April 25, showing the anomalous absorption feature, are highlighted in red.

KOI-972: A δ Sct Variable with Two Planet Candidates

We have used the HET to observe six transits of KOI-972.01, a 6.1 R_{Earth} planet candidate on a 13-day orbit about the δ Sct variable KOI-972. The star also hosts a 1.7 R_{Earth} candidate on a 7.8-day orbit. We have reduced and analyzed only two of the datasets to date, representing transits on 2011 August 3 and 16 UT. While we have not yet detected the shallow ($R_p/R_*=0.02$) transit, we have a tentative detection of non-radial oscillations of the host star in our transit data (see Fig. 5).

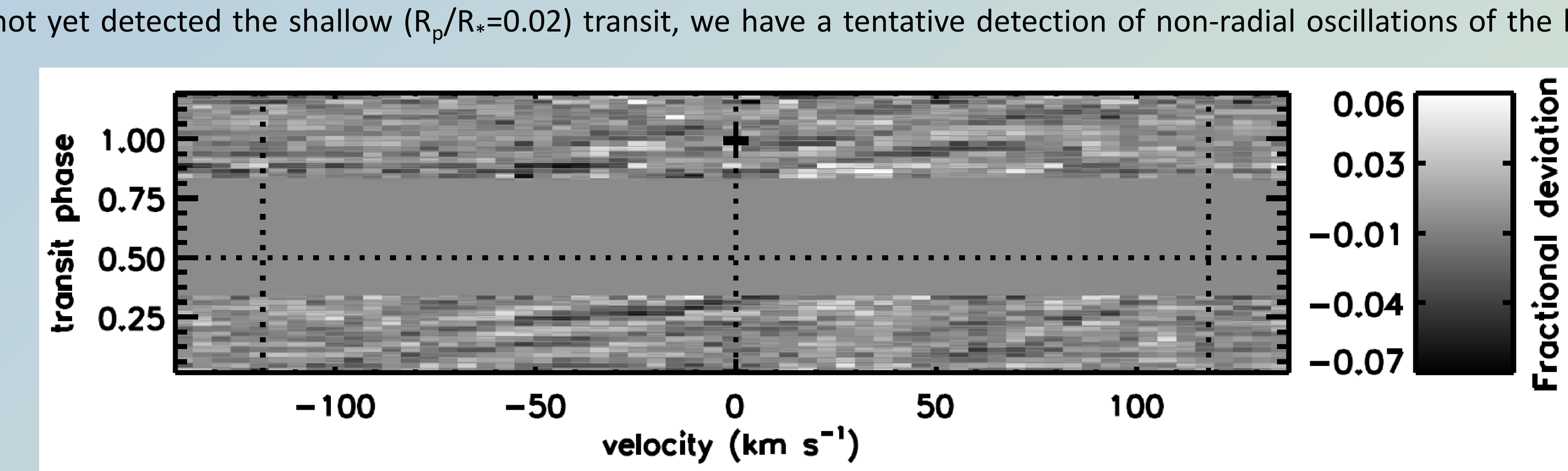

Fig. 5. Time series line profile residuals for two transit observations of KOI-972.01. The faint striations running from lower left to upper right may be non-radial oscillations of the host star.

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