CONSTRAINING THE ORBITAL ALIGNMENT OF KOI-1152.01: A SHORT PERIOD TRANSITING COMPANION WITH HIGH OBLIQUITY AND ECCENTRIC ORBIT.

T. N. Varga[1], Gy. M. Szabó[2], A. Simon[3], [1]Institute of Physics, Eötvös Loránd University, H-1117, Budapest, Pázmány P. s. 1/a. Hungary (vargatn@caesar.elte.hu), [2]Gothard Observatory, Eötvös Loránd University, H-9700 Szombathely, Szent Imre herceg útja 112, (szgy@gothard.hu), [3]Konkoly Observatory, H-1121, Budapest, Konkoly-Thege M. út 15-17. (atthys@konkoly.hu)

Introduction: Understanding the formation and evolution of our planet and solar system is a major goal of astronomy and planetary science. Until recently information regarding these topics could only be gathered from within the Solar System, however the last twenty years saw the discovery of an increasing number of extrasolar planets. By determining the properties of these planetary systems, the different theories regarding solar system formation and evolution can be tested on a very large set of planetary systems [1].

The focus of this study: The orbital planes of planets within our Solar System align well with each other, as well as with the Solar plane of rotation. This is however not always the case for exoplanets, as a multitude of planets have already been found on significantly misaligned orbits [2]. The observational determination of such relative obliquities for planets and other companions is thus a very important input for star and planetary system formation theories.

In this study we aim to reconstruct the 3D orbital parameters of the transiting companion of the Kepler star KOI-1152 using the spot activity of the host star to constrain the companion's (sky-projected) orbital inclination.

Theoretical background: One of the main methods used for detecting companions for stars is the transit method, where the light from the host star is observed while the orbiting companion seemingly passes over it, thus blocking part of its light.

This effect provides a characteristic light curve from witch several system parameters can be extracted, however it does not give any constraint to the mass of the observed companion thus distinguishing between high mass planets and low mass stars or brown dwarfs is only possible via combined photometry and Radial Velocity measurements.

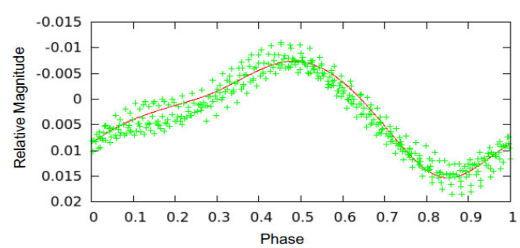
When modeling the transit light curve, most stars can be well approximated as a sphere with constant surface luminosity, however spots (active regions) or other surface features may also be present [3,4], thus breaking the previously described degeneracy of the surface brightness distribution.

The active regions of a star cause rotational modulations in the overall light curve, and if the companion eclipses some of these active regions during transit, an increase of relative flux within the transit light curve will be observable.

Star:	KOI-11521
KIC ID:	10287248
RA (J2000)	19.77971
DEC (2000)	47.3273
Spectral type:	M1
Magnitude (Kepler)	13.987
M_* $[M_{Sun}]$	0.58
R_* $[R_{Sun}]$	0.65
T_{eff} [K]	4069
$\log g$ [cm/s^2]	4.73
Parameters of the companion:	KOI-1152.01
Period [JD]	4.7222521 ± 0.0000012
T_0 [Kepler day]	111.24278 ± 0.00001
$k = R_b/R_*$	0.26720 ± 0.00073
D [hour]	3.4063
b	0.4441 ± 0.102
a [AU]	0.046
e_{min}	0.26
R_b $[R_{\mathrm{Earth}}]$	15.97
T_b [K]	620

Table.1.: *Initial parameters of the star and the companion. Retrieved from the KIC catalog 2012*

This extra information enables us to reconstruct the sky projected angle between the stellar plane of rotation and the companion's orbital plane [5,6].



Spot parameters :	Spot I	Spot II
λ [°] (latitude)	75.4209 ± 22.74	298.868 ± 9.579
β [°] (longitude)	61.4351 ± 14.42	-48.7772 ± 7.443
γ [°] (radius)	37.9204 ± 11.56	63.1745 ± 11.08

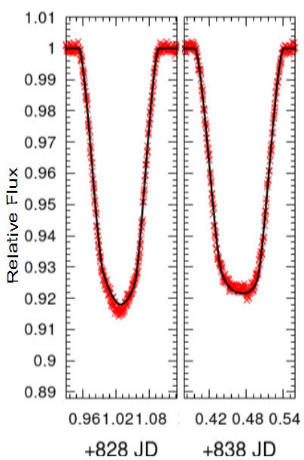
Fig.1.: *(top) out of transit rotational modulations (bottom) spot coordinates for the best fit scenario with two major active regions*

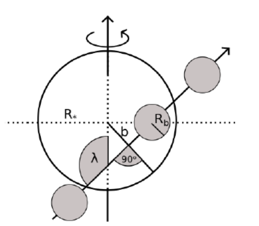
Modeling the stellar activity: We utilized the available short cadence (60 s time resolution) dataset from the Quarter 9 observations of the Kepler spacecraft (31 days total).

The observed light curve shows very intensive rotational modulations (Fig.1.), and the effects of spots are also visible within the transits (Fig.2. left). The spot distribution of the star was fitted using the SpotModeL tool (http://www.konkoly.hu/staff/ribarik/SML). A stellar inclination of 77° and T_spot=4030 K have been assumed. The mean stellar rotational period was found to be P_rot=2.93277 days.

Exploring the transit parameter space: Using the obtained spot distribution transits were modeled numerically over the spotted stellar disc. The parameters of the transit configuration were sampled randomly over a given interval (Fig.3.) with 2*10^6 points. The best fit scenario was identified using a Maximum-Likelihood method. Input parameters for the light curve modeling (Table.1.) have been obtained from the Kepler Input Catalog (KIC) for the star and the companion.

For each set of parameters the different transit light curves were calculated and fitted to the observed Kepler transits. Since the spot modeling utilizes simplifying assumptions about the structure of the active regions, the true confidence limits could not be calculated in a non-computing heavy way. This means that it is the relative topography of the parameter space which should be used for further analysis.





d [JD]	0.1252171491
$k = R_b/R_*$	0.27389516
P_b [JD]	4.72225
b	-0.5564338812
λ [°]	136.3221482509

Fig.2. *(left) Transit light curves showing different cases of spot crossing events. The black line represents the best fit result. (right) The best fit scenario and the corresponding parameter values.*

Constraining orbital eccentricity: A significant phase offset is present between the transit and the occultation of the companion. Previous studies have explored the phase curve of this particular star, and found that the phase offset corresponds to an eccentricity of at least 0.26 [7].

Conclusions: Our results show two possible scenarios, both corresponding to a nonzero obliquity [8]. Numerical bootstrap calculations are currently under way to better characterize the distribution of errors associated with the spot modeling.

The inferred high obliquity and eccentricity may result from an additional perturber present in the system, however a very young system age could also partially explain the companion's orbit and the short stellar period.

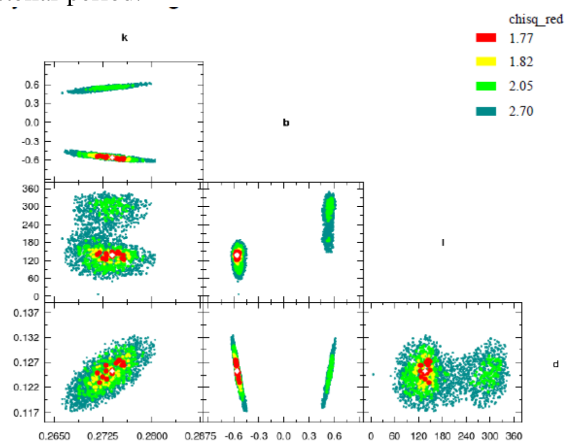


Fig.3. *The distribution of goodness-of-fit values within the parameter space*

Additional Radial Velocity observations would enable us to better clarify the planetary status of the observed companion by providing a precise mass measurement, as the extremely high irradiation associated with the short semi-major axis is known to cause significant bloating in the radii of gas giants.

Acknowledgments:
This work was made available by the "Lendület" Young Researchers Program, the OTKA K76816, K81421, K83790 and MB08C 81013 grants

References: [1] Howard et al. (2012) ApJS, 201:15; [2] Albrecht et al. (2012), ApJ 757, 18; [3] Barnes et al. (2011) ApJS, 197:10; [4] Szabó et al. (2011) ApJl, 736:L4; [5] Sanchis-Ojeda et al. (2011) ApJ, 733:127; [6] Nutzman et al. (2012) ApJl, 740:L10; [7] Szabó et al. (2013) A&A 553:A17; [8] Varga et al. (2013) Kepler Science. Conference II, *2-207*;