SUMMARY OF THE RESEARCH FUNDED BY
OTKA K-81373
Searching for multiple planetary systems by automated telescopes

1. Introduction

In agreement with the research proposal inherent to the grant, during the funding period our study focused on the following fields:

- Search for transiting extrasolar planets and trying to find multiplanetary systems with more than one transiting planets. We pursued this task within the HATNet (Hungarian-made Automated Telescope Network[1]) project.
- On the basis of 'target of opportunity', utilizing largely the HATNet database, we studied various classes of variables to determine their physical properties.

Highlighted results and their scientific impact will be described in the corresponding sections. We also add notes concerning other grant-related activities, such as dissemination of the results.

2. Transiting extrasolar planets

Extrasolar planetary systems containing transiting planets (TEPs) are exceptionally important, since, in principle, they enable us to perform a full characterization of these systems, including deeper study of the planetary properties, e.g., atmospheric composition. Among the currently verified 808[2] extrasolar planetary systems there are 328 transiting ones.[3] During the run of this project, the field witnessed a progress that was way above one could ever hope for. Almost exclusively due to the Kepler satellite, multiple transiting systems were discovered in large number, with up to 7(!) planets, all transiting the same star (see Schmitt et al., 2013). This, as most of the multiple planetary systems discovered by Kepler, belongs to a new class of "closely packed" systems, not thought to exist before the Kepler mission. It also turned out that most of the planets detected by Kepler are in the mass/size-range of Neptune, and not that of Jupiter, the type of planet size that was first sought from the ground, and the ones that gave that big push to the field that culminated in the wonderful discoveries by Kepler. Actually, from the Kepler survey it turned out that Hot Jupiters are among the least common types of planets (Howard et al., 2012).

Due to their sensitivity range, ground-based wide-field surveys (mostly SuperWASP and HAT-Net) continue to pursue relatively large and short-periodic planets, the ones that are rare, and the existence of which still poses many questions. In addition to their intriguing evolutionary history, these systems are still the prime targets for planet atmosphere studies accessible in the foreseeable future by our best available instruments (see, e.g., the planned spectroscopic mission EChO; Tinetti et al., 2012).

HATNet (Bakos et al., 2004) has been operational since 2003. The available time series photometry covers almost 20% of the sky in the brightness range of 8 mag < I < 14 mag. With substantial

[1] http://en.wikipedia.org/wiki/HATNet_Project

[2] Based on www.exoplanet.eu as of 2014.02.25

[3] Due to the large inventory of the Kepler satellite, the actual number of the candidate planetary systems with high-quality data and low false positive detection probability is much higher (i.e., greater than ~ 2000), especially for multiplanetary (i.e., multitransiting) systems, where the false positive rate might be close to zero - see Lissauer et al. (2012).

effort invested in weeding the candidates from the HATNet database and in the subsequent followup works (low/medium-dispersion spectroscopy [TRES, SOPHIE, FIES], high-precision radial velocity (RV) measurements [Keck/HIRES] and accurate photometry [KeplerCam @ FLWO]) during the run of this OTKA grant we discovered **34 planetary systems**. Table 1 summarizes the physical parameters of these systems. The corresponding references can be found in the first, numbered section of the references. In the following subsections we highlight some of the most interesting ones.

Table 1: Physical parameters of the TEPs discovered by HATNet between 2010.02 and 2014.02

Name	N_p	P_{orb}	e	M_p	R_p	M_s	R_s	T_{eff}
HAT-P-14	1	4.63	0.11	2.23	1.15	1.39	1.47	6600
HAT-P-15	1	10.86	0.19	1.95	1.07	1.01	1.08	5570
HAT-P-16	1	2.78	0.04	4.19	1.29	1.22	1.24	6160
HAT-P-17	2	10.34	0.34	0.53	1.01	0.86	0.84	5246
HAT-P-18	1	5.51	0.08	0.20	1.00	0.77	0.75	4800
HAT-P-19	1	4.00	0.08	0.29	1.13	0.84	0.82	4990
HAT-P-20	1	2.88	0.02	7.25	0.87	0.76	0.69	4595
HAT-P-21	1	4.12	0.23	4.06	1.02	0.95	1.11	5588
HAT-P-22	1	3.21	0.02	2.15	1.08	0.92	1.04	5300
HAT-P-23	1	1.21	0.11	2.09	1.37	1.13	1.20	5910
HAT-P-24	1	3.36	0.07	0.69	1.24	1.19	1.32	6370
HAT-P-25	1	3.65	0.03	0.57	1.19	1.01	0.96	5500
HAT-P-26	1	4.24	0.12	0.06	0.57	0.82	0.79	5080
HAT-P-27	1	3.04	0.08	0.66	1.04	0.95	0.90	5300
HAT-P-28	1	3.26	0.05	0.63	1.21	1.03	1.10	5680
HAT-P-29	1	5.72	0.10	0.78	1.11	1.21	1.22	6090
HAT-P-30	1	2.81	0.04	0.71	1.34	1.24	1.22	6300
HAT-P-31	1	5.01	0.25	2.17	1.07	1.22	1.36	6065
HAT-P-32	1	2.15	0.00	0.86	1.79	1.16	1.22	6210
HAT-P-33	1	3.47	0.00	0.76	1.69	1.38	1.64	6450
HAT-P-34	1	5.45	0.44	3.33	1.20	1.39	1.54	6442
HAT-P-35	1	3.65	0.03	1.05	1.33	1.24	1.44	6096
HAT-P-36	1	1.33	0.06	1.83	1.26	1.02	1.10	5560
HAT-P-37	1	2.80	0.06	1.17	1.18	0.93	0.88	5500
HAT-P-38	1	4.64	0.07	0.27	0.83	0.89	0.92	5330
HAT-P-39	1	3.54	0.00	0.60	1.57	1.40	1.63	6430
HAT-P-40	1	4.46	0.00	0.62	1.73	1.51	2.21	6080
HAT-P-41	1	2.69	0.00	0.80	1.69	1.42	1.68	6390
HAT-P-42	1	4.64	0.00	1.04	1.28	1.18	1.53	5740
HAT-P-43	1	3.33	0.00	0.66	1.28	1.05	1.10	5650
HAT-P-44	2	4.30	0.07	0.39	1.28	0.94	0.98	5295
HAT-P-45	1	3.13	0.05	0.89	1.43	1.26	1.32	6330
HAT-P-46	1	4.46	0.12	0.49	1.28	1.28	1.40	6120
HAT-P-49	1	2.69	0.00	1.73	1.41	1.54	1.83	6820

Notes: – Units for the period, planet mass and radius are in [days], [Jupiter mass, radius]. For the star the units are [solar] and [K] for T_{eff}. – In most cases low eccentricities have large relative errors, indicating circular orbits. – For HAT-P-31 the corresponding paper mistakenly acknowledges our previous grant, so we do not list that publication at the OTKA web site ...

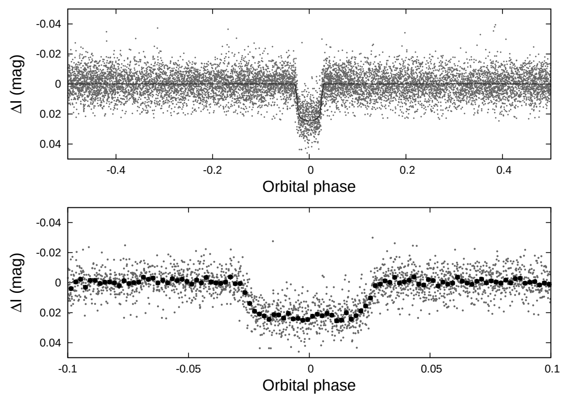


Figure 1: *Top: Unbinned light curve of HAT-P-32 from the HATNet database folded with the orbital period (see Table 1). The solid line shows a transit-model fit to the light curve. Bottom: Zoomed-in view of the transit, with the dark points showing the light curve binned in phase with a bin size of 0.002 .*

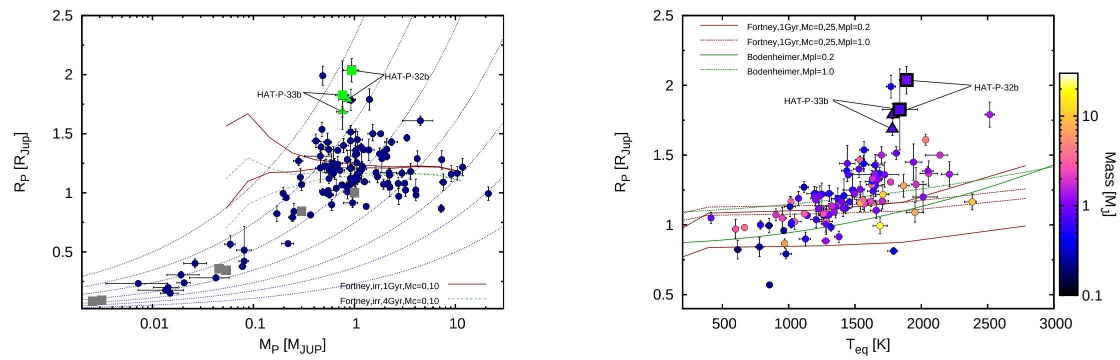


Figure 2: *Planet radius versus planet mass and equilibrium temperature. Planets are known at the time of the discovery of HAT-P-32, 33 are plotted. Left: Mass - radius: for HAT-P-32b, 33b the triangles indicate the parameters for circular orbits, while the squares indicate the parameters when the eccentricity is allowed to vary. Filled circles are all other TEPs, and filled squares are solar system planets. We show iso-density lines (dotted lines running from lower left to upper right) and irradiated theoretical planet mass – radius relations from Fortney et al. (2007). Models are for core masses of 0 and 10 $M_{\rm Earth}$ (upper and lower relations) and for planet ages of 1Gyr and 4 Gyr. Right: Equilibrium temperature - radius diagram for TEPs with $M_{\rm p} > 0.1 M_{\rm J}$. Notation for HAT-P-32b, 33b is the same as on the figure to the left. We introduced mass-color code as given in the side bar. We show theoretical relations from Fortney et al. (2007) and Bodenheimer et al. (2003). Models for both 0.2 and 1.0 $M_{\rm J}$ planets are shown with different core masses of 0 and 25 $M_{\rm Earth}$.*

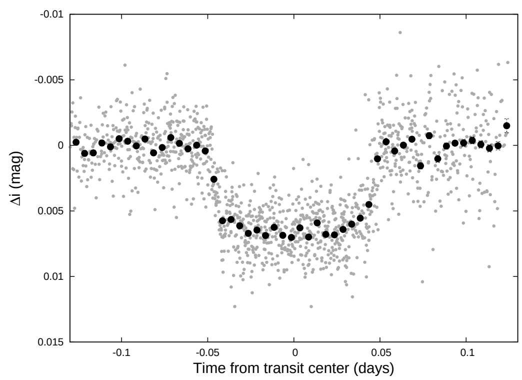
2.1 Highly-bloated planets

The discovery of the very first TEP (HD 209458) in 2000 (Charbonneau et al. 2000) has already brought up the issue of the high overall radii of Hot Jupiters. In the case of HD 209458 this was 'only' $\sim 20\%$, but after that even higher differences were found between the model and observed values. Although some of the differences have been successfully accounted for by mechanisms such as stellar insolation, tidal heating and ohmic dissipation, the issue is largely considered today as unsolved, especially with the growing number of planets with more extensively inflated radii.

HAT-P-32, 33 had already been sitting in our candidate database for several years, when we decided to examine them again, primarily because of their high-quality light curves (see Figure 1) and noisy, but definitely periodic radial velocity variations. The depth of the transit basically explains the main source of our hesitation to invest more time in this target: the estimated size of the planet would have been ~ 1.8 $R_{\rm J}$, which is way beyond the expected size of a HJ with a mass of ~ 0.9 $M_{\rm J}$. Because of the large RV jitter in both objects, standard spectral bisector method to reject blend scenarios was not convincing. Therefore, we opted to a direct light curve (LC) modeling, similar to the one used in the verification of some of the Kepler planets (Torres et al., 2011). We found that all of the (star-star) blend configurations produce features on the LCs that could not escape our attention (see [11] for further details).

Figure 2 shows the planets' positions on the M–R and T_{eq} (equilibrium temperature)–R diagrams. It seems that less massive planets are more vulnerable to effects exciting larger planet radii. We note that there are 3 more planets among the 33 planets discovered in 2011-2014 that have radii greater than 1.5 R_J. These are HAT-P-39, 40 and 41 (not shown in the figure).

2.2 In the Neptune regime



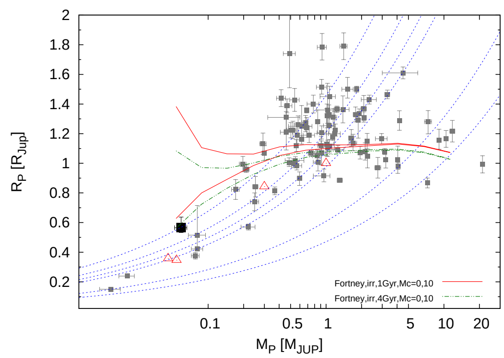


Figure 3: Left: *Combined Sloan i-band KeplerCam light curve of HAT-P-26 folded with the period $P =$ 4.235 days. The dark filled circles show the light curve binned and folded in time with a bin size of 0.005 days. The median uncertainty on the binned points is 0.19 mmag.* Right: *M-R diagram of known TEPs (small filled squares). HAT-P-26b is shown as a large filled square. Overlaid are Fortney et al. (2007) theoretical planetary mass-radius curves interpolated to the solar equivalent semi-major axis of HAT-P-26b for ages of 1.0 Gyr (upper, solid lines) and 4 Gyr (lower dash-dotted lines) and core masses of 0 and 10 M_E (upper and lower lines respectively), as well as isodensity lines for 0.4, 0.7, 1.0, 1.33, 5.5, and 11.9 gcm^{-3} (dashed lines). Solar system planets are shown with open triangles.*

There are 100 planets (most of them in multiplanetary systems) with masses under 35 M_E ($\sim$twice of the mass of Neptune and one tenth of the mass of Jupiter). Most (i.e., 92) of them come from the Kepler mission, the remaining come from the following sources:

- **CoRoT-7b** – CoRoT satellite (Queloz et al., 2009)
- **55 Cnc e** – MOST micro-satellite (Winn et al., 2011)
- **HD 97658 b** – MOST micro-satellite (Dragomir et al.,2013)
- **GJ 3470 b** – discovered by HARPS (precise ground-based radial velocity spectrograph); transit detected from the ground by Bonfils et al. (2012)
- **GJ 1214b** – discovered by the ground-based MEarth project (Charbonneau D. et al., 2009)
- **GJ 436 b** – discovered by Keck/HIRES (precise ground-based radial velocity spectrograph); transit detected from the ground by Gillon et al. (2007)
- **HAT-P-11b** – discovered by HATNet (Bakos et al. 2010)
- **HAT-P-26b** – discovered by HATNet (Hartman et al. 2011)

We see that 5 from these systems were discovered as TEPs from the ground, but only the MEarth and HATNet planets resulted from a systematic ground-based photometric search (we also note that MEarth uses 40 cm, whereas HATNet uses 11 cm diameter telescopes).

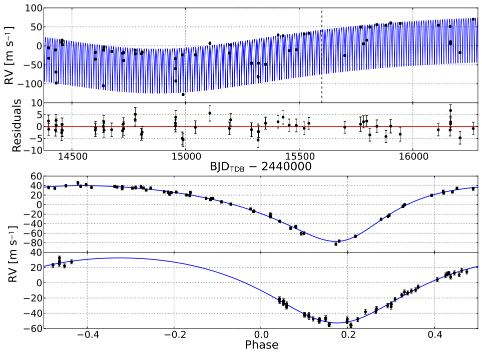


Figure 4: Top: Keck/HIRES RV measurements for HAT-P-17 from Fulton et al. (2013) as a function of time. The best-fitting two-planet model is shown by continuous line. Data to the right of the vertical dashed line are from Fulton et al. (2013), and data to the left are from our paper of Howard et al. (2012). Bottom: The same RV measurements phase-folded to the orbital ephemerides of the transiting planet 'b' (upper) and the RV planet 'c' (lower). Phase zero corresponds to the time of mid-transit (for planet 'c' this is the computed moment of time from the available RV data).

HAT-P-26b orbits a K1-type star with a period of 4.235 days. As expected from the low amplitudes of mere 8 ms^{-1} and 7 mmag respectively, of the radial velocity and transit curves, the mass and radius of the companion should be rather small. From the global analysis including the radial velocity, photometric, spectroscopic data and stellar evolutionary models, we derived a mass and radius of 0.06 M_J and 0.57 R_J, respectively (for further details see [17]). Interestingly, the orbit turned out to be different from circular, with an eccentricity of 0.124 ± 0.06, which may suggest a presence of a perturber (planet or star) or may just be the result of a past close encounter with another planet. We show the low-amplitude transit and the position of the planet in the M-R diagram in Figure 3. We have 3 more planets in the sub-Saturn mass range. These are HAT-P-18, 19 and 38.

2.2 Multiplanetary systems

Multiple transiting systems are the most precious ones among the currently accessible planetary systems. Unfortunately, so far only the Kepler satellite was able to detect this kind of systems. All of them are either too small in size or have too long periods, usually inaccessible by ground-based small-aperture telescopes. Although HATnet already found 2 hot Neptunes, we could not find so far additional transiting planets in these or other systems. This may be the consequence of the lack of closely-packed multiplanetary systems with Hot Jupiters (or similar large mass companions – see Ogihara et al., 2013). However, we found 3 systems that contain long-period planetary companions detected by our long-term radial velocity monitoring. HAT-P-13 was highlighted in our earlier summary report on OTKA K-60750. Here we report the discovery of two additional systems of this kind.

The transiting planet HAT-P-17b by itself is interesting, since it has an orbital period of 10.34 days (see [8]). After HAT-P-15b, HAT-P-17b is our second planet discovered so far with orbital period longer than 10 days. The observed long-term trend in the RV data first suggested that HAT-P-17c had a period of ∼1600 days, but current data by Fulton et al. (2013) imply that the period could be much longer (maybe as long as 10-40 years). Nevertheless, the data still support the planetary status for 'c', with a mass of 2–6M_J.

We have rather convincing evidence that HAT-P-44 has also another planetary component, so far detected only in the radial velocity data (see [3]). Although the period is ambiguous with a factor of two (220 days or 440 days), the mass should be under 4M_J in both cases. We also have HAT-P-46c, but the evidence for a second planet is weaker here, although this system might be more interesting, as planet 'c' might have a period as short as 80 days.

We note that in the current paper of Knutson et al. (2013) there are further systems (including several of those discovered by HATNet) listed as likely multiplanetary hosts of the above kind (including several of those discovered by HATNet). We stress that, from the ground-based photometric surveys so far it is only the HATNet project that discovered multiplanetary systems in

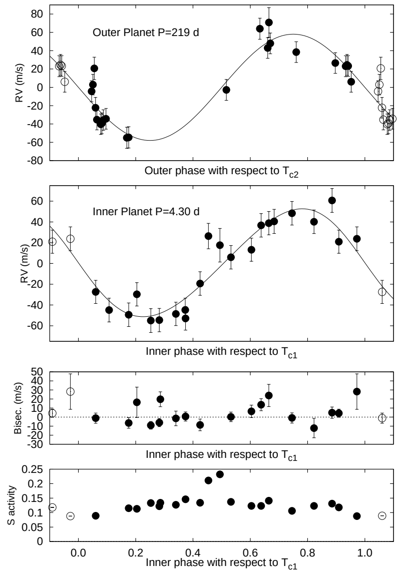


Figure 5: Decomposition of the RV variation of HAT-P-44 into the long- and short-period components (shown, respectively, on the first and second panels from the top). Overplotted are the respective components of the best-fit orbital model. Zero phase corresponds to the time of mid-transit (for long-period planet 'c' we assumed an edge on orbit – the transits of this planet have not been detected). Observations shown twice are plotted with open circles. The lower two panels show the variations of the bisector spans (BS) and the chromospheric activity index S. Both of these quantities are phased by the orbital period of the transiting planet 'b'.

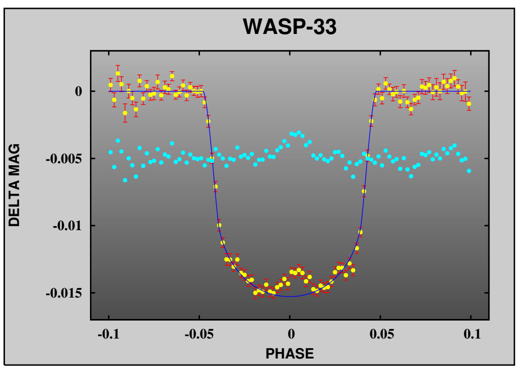


Figure 6: Transit light curve obtained by summing up 32 light curves. We combined the data in 0.002 phase units (yellow dots). Error bars show the $\pm 1\sigma$ ranges of the bin averages. Continuous line shows the reference model light curve. The light blue dots in the middle of the plot show the residuals (arbitrarily shifted) for the dataset without prewhitening by the δ Scuti components.

which one of the components is a transiting one.

2.3 The transit anomaly of WASP-33

WASP-33 was discovered by the SuperWASP project, although the target was also on our candidate list as HTR167-010. We accumulated an ample amount of radial velocity data in spite of the fact that the target is a fast-rotating A-type star, in which case RV data may become fairly inaccurate, thereby making it difficult both the verification and the derivation of the system parameters. Nevertheless, our data allowed us to perform a deeper analysis of the system that we described in [4].

Together with some other transiting extrasolar planets, e.g., Kepler-17 and HAT-P-11, WASP-33 exhibits a recurring anomalous feature, a mere 0.2% brightening near the center of the transit (see Figure 6). Discovery of such a small anomaly was made possible by the utilization of some 30 amateur observations of separate transit events carried out by small telescopes. This is the fastest rotating star with known extrasolar planet. The planet orbits its host star in every 1.2 days. The direction of the motion is opposite to the rotation of the star. The physical cause of the anomaly is highly puzzling, since stars of this type - a metallic-line A-type star - usually do not carry spots, the customary explanation for transit anomalies.

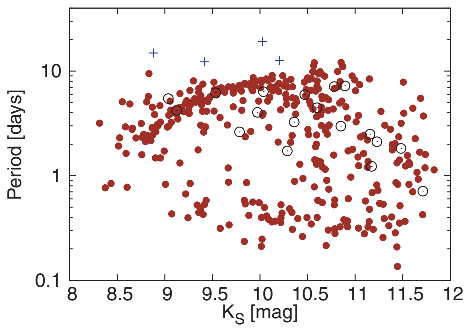


Figure 7: Period versus 2MASS K magnitude for the rotational variables discovered largely by HATNet in the open cluster Pleiades. Filled circles show well-documented cluster members, open circles correspond to new candidate members which passed our selection criteria. Crosses show candidate members that passed the previous selections, but have periods that are too long to be cluster members.

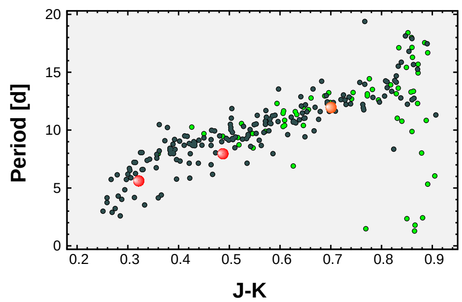


Figure 8: Period–(J−K) plot for the open clusters Praesepe (dark filled circles, corresponding to the variables discovered largely by HATNet) and for the Hyades (light filled circles, Delorme et al., 2010). The RV planets (Quinn et al., 2012, 2013) are shown by the darker- and lighter-shaded spheres for the Praesepe and Hyades, respectively.

3. Rotating and pulsating variables

The archives of the wide-field transit surveys enable us to investigate a wide class of variables that were previously largely unattended, due to the lack of devoted monitoring of the individual objects for a sufficient long period of time with an ample level of precision. Photometric variability is one of the topics recently attended also by other TEP survey projects (e.g., by SuperWASP – Delorme et al.,2010, by Kepler mission – Meibom, 2011).

In [16] we surveyed the 27560 field K to M stars and searched for variables. We securely identified 1568 variables, most of them proved to be rotational ones due to stellar activity (spots). In [21] we present the rotational periods of 368 stars in the Pleiades. This sample increased the number of known rotational variables in this cluster by a factor of 5. Most of the variables follow a well-defined period - color relation (see Figure 7), particular for open cluster rotation rates for stars that passed $\sim 50 - 100$ Myr after they landed on the main sequence and disconnected from the protostellar cloud in which they were born.

In another paper [in preparation] we visit another well-known open cluster. In Praesepe (M44) we found 180 rotation variables (thereby triple the number of available rotation rates for this cluster). Similarly to the Pleiades, most of these stars also follow a fairly tight period - color relation (see Figure 8). A comparison with the another cluster Hyades from Delorme et al. (2010) shows that both clusters have the same gyrochronological ages. Interestingly, both clusters host planetary systems with Hot Jupiters. Based on the rotation ridges in the (color,P) plane, we found some hints that planet host stars rotate faster than single ones.

In [29] we investigated AC And, the first triple-mode radially pulsating star discovered by Fitch & Szeidl (1976). Above 30 components were found down to the amplitude of 3 mmag. Some of these were not the linear combination of the 3 main components, suggesting the possibility of other, possibly non-radial pulsation components. We detected a period increase in all three components that supports the Pop I classification of this variable.

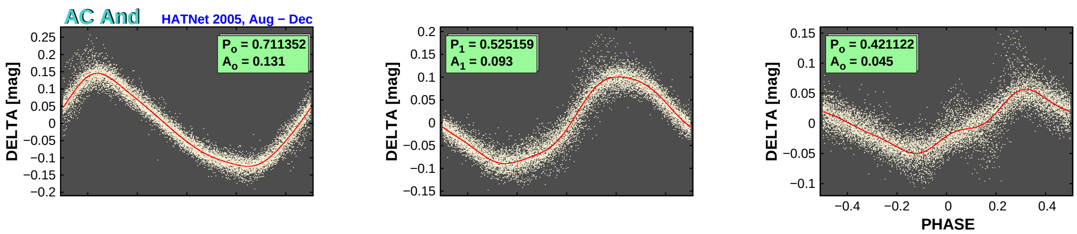


Figure 9: Individual modes of pulsation. The data are fitted with the complete 3rd-order 3-frequency combinations, then, the individual modes are computed by prewhitening the data with the corresponding 'cross terms'. The red line is a 4th-order Fourier fit to the light curves. The extra scatter in certain phases is due to frequency components not matched by the 3rd-order combinations.

4. Scientific impact and related activities

We have published 28 papers (including some conference proceedings) acknowledging the support of this grant. As of 2010.02.20, we received some **240** independent citations on the above publications.

Concerning project-related activities, we note the following. Gaspar Bakos received the Pierce Prize and several other awards and fellowships (the Muhlmann Award, the Alfred P. Sloan Research Fellowship, etc.). Geza Kovacs was an Oliver L. Benediktson endowed chair for astrophysics at the University of North Dakota between 2012 and 2014. He gave numerous seminars and public talks at UND and at other universities in the US. Istvan Dekany presented results related to the variable star inventory of the VISTA survey in 4 conferences.

We temporarily employed PhD student Gergely Hajdu for performing research in the field of RR Lyrae stars. Tamas Kovács was employed as a researcher from February 1st, 2011 till the end of the project. András Pál was a temporal employee as a researcher. During the absence of leave of the PI (between May, 2012 and September, 2013), Imre Tóth took over his role.

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[4]Except for [12], numbered publications are the ones which acknowledge this grant (OTKA K-81373). Papers with more than five authors are referred to 'First 5 authors et al.', except if the PI is one of the co-authors and the names of the first five authors do not include that of the PI. In this case all authors up to the name of the PI are listed.

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