Summary of the research funded by
OTKA K-60750
Extrasolar planet and variable star research by wide-field photometry

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 within the HATNet (Hungarian-made Automated Telescope Network[1]) and WHAT (Wise HAT[2]) projects.
- Studying various classes of pulsating 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 instrument maintenance and dissemination of the results.

2. Transiting extrasolar planets

Transiting planets (TEPs) are especially important among the currently known 429 extrasolar planets, discovered mostly by radial velocity (RV) techniques. Analysis of TEPs yields a wealth of information (from orbital parameters to atmospheric characterization) as compared to their non-transiting counterparts (see the excellent review of Winn 2010). Therefore, it is important to discover TEPs in large numbers to understand the cause of their wide variety in terms of the orbital and physical properties. Because of the demanding followup observations required both for the verification (i.e., excluding blend scenarios) and for the subsequent deeper analysis (e.g., transmission spectroscopy or occultation observations) are exceedingly difficult for fainter objects, the discovery of bright TEPs remain an important pursuit for wide-field small-telescope surveys such as XO, SuperWASP and HATNet. Because of the faint object dominated samples, this is true also for the space projects CoRoT and Kepler, even though they will continue to discover interesting and even record-breaking planets (see Queloz et al. 2009, and Borucki et al. 2010 and references therein).

The wide-field survey projects HATNet and WHAT have been operational since 2003-2004. More than 11% of the sky have been surveyed so far. The number of science frames are over one million. The number of light curves extracted from these frames is also over one million. These light curves are sampled at a cadence of 5.5 min, well suited for transit search and other variability studies. The data reduction pipeline and analyzing routines have evolved over the years (see Bakos et al., 2004 [system description]; Pál & Bakos 2006 [astrometry]; Bakos et al., 2010 [EPD]; Kovács et al. 2002 [BLS], 2005 [TFA]), which has led to the discovery of 13 TEPs between 2006 and 2010. All these ensure the strong competitiveness of the HAT project in comparison with other transit search projects (see Table 1).

Wide-field small-telescope projects started bearing fruit from 2006. From the 69 TEPs known today, only 11 were known prior to 2006, mostly due to the microlensing/variability project OGLE. In the following we briefly summarize the contribution of the HAT project to this field made in part through the support of this research grant.

[1] http://www.cfa.harvard.edu/~gbakos/HAT/)
[2] http://wise-obs.tau.ac.il/~what

Table 1: Number of discovered planetary systems by various projects[a]

Project	N_p	Location
WASP :	[b]18	La Palma, SAAO (South Africa)
HAT :	[b,c]13	Hawaii, Arizona, Izrael
TrES :	[d]4	Palomar Obs., Lowell Obs.
		Teide Obs. (Canary Island)
OGLE :	8	LCO (Chile)
XO :	5	Hawaii
CoRoT :	7	Space
Kepler :	5	Space
SWEEPS :	2	Hubble, space
Mearth :	1	FLWO, Arizona
SSO :	1	Siding Spring Obs., (Australia)
[e]RV :	6	Various observatories

Notes: (a) Based on *http://exoplanet.eu* as of 2010.02.22; (b) WASP-11=HAT-10 has been added to both HAT and WASP; (c) Including the contribution to the discovery of 2 planets by WHAT; (d) TrES-3 is a joint discovery of TrES and HATNet; (e) Planets discovered by photometric surveys of known radial velocity planets.

2.1 In the Main Stream

From the 13 HAT planetary systems discovered so far, 4 belong to the "main stream" hot Jupiters. They have periods between 2.8 and 3.9 days and masses between 0.8 and 1.1 M_J. These systems are **HAT-P-5, 6, 8** and **9** (see refs. [3], [19], [20] and [25]). In spite of that these are "average" hot Jupiters, we note that P-8 is one of the "nicest behaving" TEPs in terms of the very low level change in the spectral correlation line bisector (BS, a measure of the level of symmetry of the line profiles). The ratio of the BS and RV amplitudes is only 3%. As is known, low-level uncorrelated/noisy variation of the bisector span is one of the important criteria of declaring a candidate to be a planet. Furthermore, P-9 is also remarkable for the following reasons. The host star of P-9b has a relatively large rotational velocity ($v_{rot} \sin i = 12$ kms^{-1}). This implies a very large amplitude Rossiter-McLaughlin (R-M) effect of 100 ms^{-1}, larger than the amplitude of the orbital Doppler effect. With $V = 12.3$ mag, this system is also among the faintest ones discovered by wide-field surveys. Yet another property is that P-9b has a rather low density of 0.35 gcm^{-3}. Two more planets (HAT-P-1 and P-4 – refs. [2] and [14]) have similarly low densities – for some period near record holders. Currently, the three outstandingly low-density planets are TrES-4b, Kepler-7b and WASP-17b, with densities of 0.21, 0.17 and 0.13 gcm^{-3}, respectively (Mandushev et al., 2007; Latham et al. 2010; Anderson, D. et al., 2010).

2.2 The sub-Jupiter regime

There are 3 planets with masses 'characteristically' smaller than 1 M_J, but greater that of the Saturn (i.e., $M > 0.3$ M_J): HAT-P-1 (0.52 M_J, also a 'bloated' planet, discussed later), **HAT-P-3** (0.60 M_J, [28]) and **HAT-P-10**=WASP-11 (0.46 M_J, [5]). Except for HAT-P-1b, that has a G0 host star, the two others have K-type dwarf hosts, in part aiding both the easier detection and the subsequent analysis. Except for their masses, these are "main stream" hot Jupiters discussed above.

2.3 Orbiting retrograde (is it easy?)

'Normally' **HAT-P-7** [22] would have been classified in this summary as a "Main Stream" planet ($M = 1.8$ M_J, $R = 1.4$ R_J, $P = 2.2$ days). However, there are two good reasons why the system deserves more attention than similar other planets: (i) this is in the field monitored by the Kepler satellite; therefore, it is an exciting target for ultra-precise followup observations; (ii) the R-M effect measured by two independent groups (Narita et al. 2009; Winn et al. 2009) strongly suggests that the orbit of the planet is retrograde in respect of the star's rotation. To demonstrate these results, we show the recent Kepler light curve in Fig. 1 (Welsh et al. 2010). We see the fine structure of the observed flux variation, including the 0.01% drop in intensity due to the occultation of the planet by the star and the combined effect of the reflected light of the planet and the ellipsoidal variation of the star, excited by the tidal force of the relatively high mass and the close proximity of the planet. The R-M effect is shown in Fig. 2. The cause of the tilted orbit is *unclear* at this moment, but there are candidate effects such as close encounter with another planet or planet-planet scattering, followed by tidal circularization. The observed radial velocity drift by Winn et al. (2009) might suggest the presence of a third body in the system, perhaps related to the tilt of HAT-P-7b.

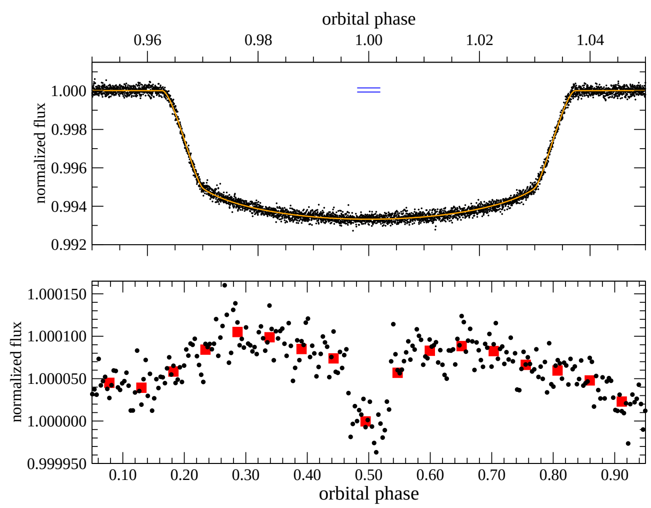

Fig. 1. The transit (upper panel) and the full folded/binned light curve (lower panel) of HAT-P-7 measured by the Kepler satellite (Welsh et al. 2010). The occultation and the out-of-transit variation due to the combined effects of tidal force exerted on the star by the planet and the reflected light of the planet are detected with very high significance. Continuous line show the model fit, dots and squares correspond to different binnings. The equal sign in the upper panel indicates the range in the lower panel.

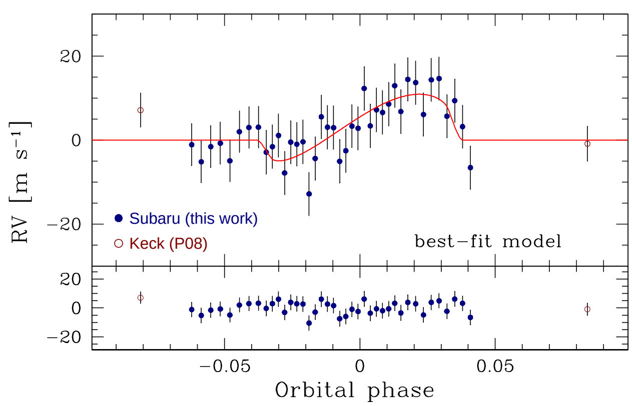

Fig. 2. The Rossiter-McLaughlin effect of HAT-P-7, indicating the retrograde orbital motion of the planet (see Narita et al. 2009).

2.4 Being (somewhat) oversized

Building models that are capable of reproducing the observed basic parameters (mass and radius) of Hot Jupiters proved to be a difficult task. The first TEP (HD 209458b) has already posed the problem in explaining a $\sim$ 20% excess in radius. Interestingly, our first planet **HAT-P-1b** [2] showed similar anomaly, together with the later discovered **HAT-P-4b** [14]. Several models have been constructed over the years, including improved treatment of tidal heating, opacity and irradiation effects. Although these models are now capable of explaining the observed parameters of most of the planets, there remain exceptions, such as TrES-4b and WASP-12b (Ibgui, Burrows & Spiegel 2010; Baraffe, Chabrier & Barman 2010; Miller, Fortney & Jackson 2009). We also note that a more accurate followup survey of these planets might lead to a similar downward radius correction as we witnessed in the case of HAT-P-1b (Winn et al. 2007).

2.5 In the Heavy-Weight League

Besides the exciting goal of finding small mass/size planets, the brown dwarf region and below, down to Jupiter mass is also a territory where accurate empirical data were scarce or non-existent just before a few years ago. From the 69 TEPs known today[3], there are only 9 with masses between 2 and 5 M_J and only 6 greater than 5 M_J. In this latter class, there is only one planet (CoRoT-3) with a mass above the nominal brown dwarf limit of $\sim$ 15 M_J. HAT-P-2b [1] is orbiting an evolved F star with a period of 5.6 days, toward the long period tail of the period distribution of TEPs. Its orbital eccentricity of 0.51 is also quite extreme. Because of the near Jupiter radius, together with the 5 similar planets mentioned above, HAT-P-2b is among the densest TEPs known today ($\rho = 7.3$ gcm^{-1}, vs. the lightest ones with $\rho \sim 0.15$ gcm^{-1}). It is important to note that the discovery of HAT-P-2b was not easy, because the host star is an evolved F star with large radius. The dimming is merely $\sim$ 6 mmag and, in the early observations it was heavily biased by systematics. With the aid of TFA filtering (Kovács et al. 2005) and, quite unequally, utilizing the fact that the target is in the overlapping region of three different HAT fields, using all available 26000 data points, we were able to detect the signal with very high significance (see Fig. 3).

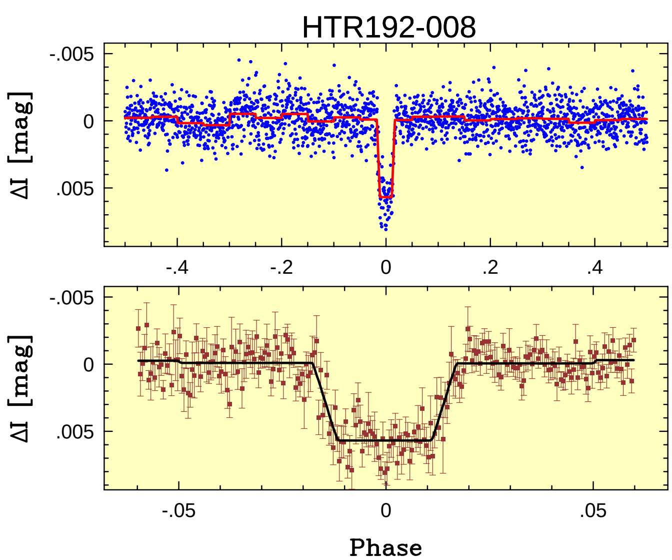

Fig. 3. Folded/binned light curve of HAT-P-2(=HTR192-008) obtained from the 26K data points collected by the HATNet and WHAT telescopes in three HAT fields. Continuous lines are the best fitting trapeze transit approximations.

2.6 In the Light-Weight League

Currently, there are 6 TEPs known under the Saturn mass limit (i.e., 0.3 M_J). Two of them (CoRoT-7b, and GJ 1214b) are in the super-Earth (few times M_E), three (GJ 436b, **HAT-P-11b** and Kepler-4b) are in the super-Neptune (somewhat larger than 0.05 M_J = 16 M_E) and only one (**HAT-P-12b**) in the sub-Saturn regime ($M < 0.30$ M_J). These objects represent perhaps the most interesting and observationally challenging TEPs. These discoveries are also encouraging for future efforts to be invested in searches for smaller near-Earth-size planets. It is also interesting to note that these TEPs were discovered by using a range of telescopes, from the low-budget HATNet to the expensive space projects.

[3]see http://exoplanet.eu

The discovery of HAT-P-11b [7] was very challenging due to photometric systematics, crowdedness of the field (given that it is in the Kepler field of view) and due to the small transit depth of 0.0035 mag (in spite of the host star being a K dwarf, the small radius of half of the Jupiter, yields a very shallow transit). Fig. 4 shows the composite light curve obtained by the many followup works done at the Whipple Observatory, AZ.[4] HAT-P-11b has the longest period of 4.9 days and the most eccentric orbit among the 6 low-mass planets listed above. The high eccentricity suggests the presence of another body (possible a planet) in the system. Observations are continuing for this target. The radial velocity data support that we have additional body (or bodies) in the sytem. We also have sufficient stellar activity that further complicates the proper understanding of the radial velocity data. Since the system is observed by the Kepler satellite, a very deep study of the system will be possible by using the precise photometric data.

HAT-P-12b [12] is also orbiting around a K dwarf. With a mass of 0.21 M_J and a radius close to the one of Jupiter, its structure is resembling very much to that of the Saturn, namely it has a very small core of less than 10 M_E (15% of the total mass, dominated by H/He). This is opposit to what we see in the case of HAT-P-11b, which is a heavy element-dominated planet. In [12] we contemplate that the incidence rate of Saturn-type planets around late-type stars might be low, because these are relatively easy to detect due to the favorable planet to star radius ratio.

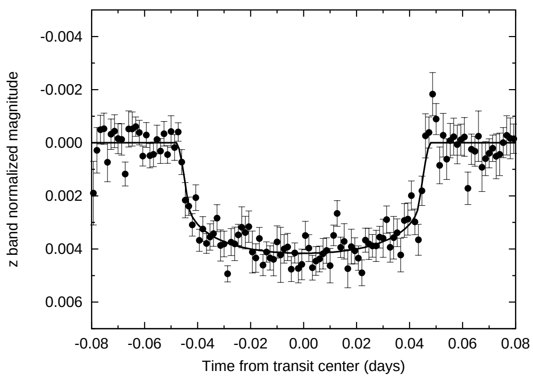

Fig. 4. Folded/binned light curve of HAT-P-11 by using the followup observations made by KeplerCam at FLWO. The continuous line is the best-fitting model light curve.

2.7 The odd couple

With its 2.9 days period, **HAT-P-13** [6] started as a "normal" hot Jupiter candidate. Followup observations accumulated, light curve with its 0.007 mag transit depth and boxy shape seemed to be encouraging. Problems emerged when the the accumulation of the radial velocity data continued longer than 'usual' in planet discovery practice. A few large outliers completely ruined the Keplerian solution corresponding to a single planet. Fortunately, the target was not put aside as 'problematic' and radial velocity observations continued well over a period of a year. Gradually, a physically sound solution emerged: the outlying RV data points turned out to be the result of the strong wobbling exerted on the host star, when an outer orbiting ~ 15 M_J-mass substellar object (most probably a planet) passes by the star at 0.36 AU with a period of 429 day. If we properly decompose the RV data into two Keplerian orbits, we get that the orbits are nearly aligned along their apses (although with a substantial error of 40 degrees due to the limited data) and that the outer orbit of planet 'c' is highly eccentric whereas the one of planet 'b' (the transiting hot Jupiter) is nearly circular (see Figs. 5 and 6).

Two recent modeling of the system has led to interesting conclusions concerning planetary structure and orbital configuration. Batygin et al. (2009) conclude in a nearly immediate response to

[4] It is important to note that, as part of the followup effort needed for the verification of the planet, one of the transits of this target was also observed at the Konkoly Observatory by using the 90/60cm Schmidt telescope at the Piszkés mountain station.

the discovery that the system is in a tidal equilibrium. This may happen in a situation when the apses are aligned – apparently this is the one actually observed for HAT-P-13b,c (see Fig. 6). They showed that once the eccentricity of the inner planet will be measured with higher precision, the configuration will enable us to compute the mass distribution, tidal dissipation factor and core-mass of the inner planet with an accuracy never seen before. Yet another work by Mardling (2010), based on full dynamical modeling (including tidal dissipation and obliquity), predicts that the orbital planes are most probably of low mutual inclination (i.e., a chance for observing the transit of planet 'c').

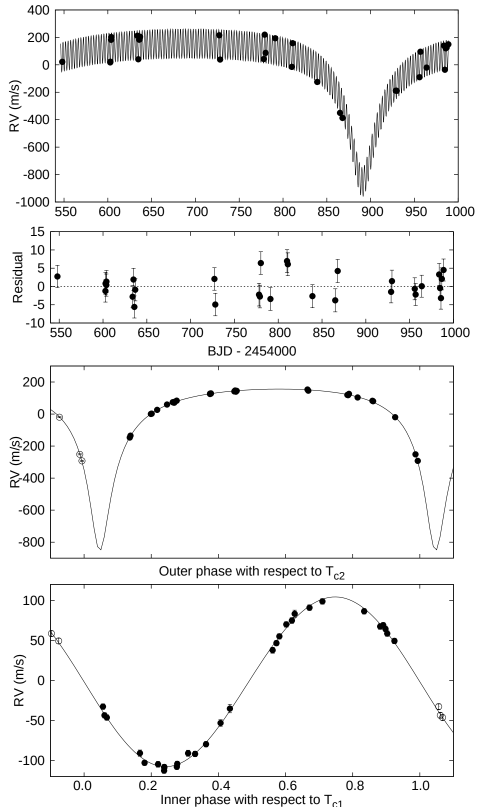

Fig. 5. Decomposition of the radial velocity data for HAT-P-13. *Top:* Observed radial velocities (dots) superposed the best-fit model including the short- and long-periodic components of the stellar wobble. *Top-middle:* Residuals between the model and the data. The RMS of the fit is 3.4 ms^{-1}, which is larger by $\sim$ 1.7 ms^{-1} than the overall formal error of the measurements. The excess scatter is probably due to some low level stellar activity. Please note the change in the vertical scale in respect of the top panel. *Bottom-middle:* The long-period ($P_c = 428.5$ days) component of the radial velocity variation. The curve is strongly non-sinusoidal, implying a very eccentric orbit of $e = 0.7$ for planet "c". *Bottom:* The short-period ($P_b = 2.916$ days) component of the radial velocity variation. The curve is nearly sinusoidal, with a signature of a very small eccentricity of $e = 0.021 \pm 0.009$ for planet "b".

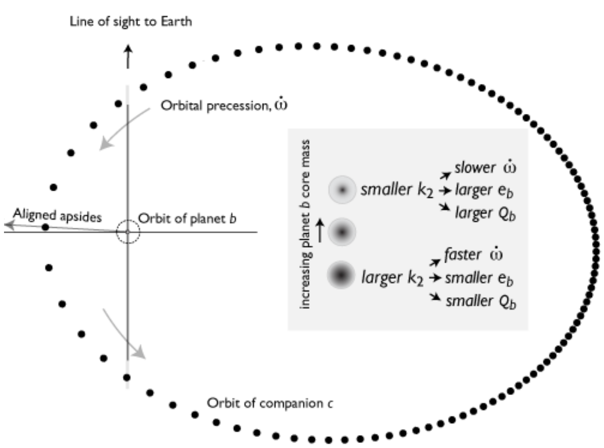

Fig. 6. Orbital configuration of HAT-P-13b,c and the effect of the internal structure of planet "b" on the observable orbital and theoretical dissipation parameters. The Love number k_2, determining the degree of the central condensation of planet "b", can be confined by accurately measuring e_b, the eccentricity of the inner planet.

3. Pulsating stars, data analysis and others

In addition to the search for extrasolar planets, we continued our studies on pulsating stars and signal analysis, in particular emphasis on the applicability of the trend filtering algorithm (TFA). We also worked on some other topics, related to this grant, but perhaps less easy to classify. For instance, we presented system description of HATNet and WHAT in [4] and [26], respectively. The result of a general variability search performed on a single WHAT field is given in [24]. Interesting 'by-products' of the transit search are presented in [8] (description of an M/F binary – valuable for examining the low-mass end of the Main Sequence, but classical 'impostors' in transit search projects); in [21] (accidental joint discovery of TrES-3 by HATNet and TrES) and in [23] (a late publication of the independent discovery of XO-5 – a potential HAT-P-#, would that be published earlier).

3.1 Pulsating stars

By using the OGLE BVI colors in the Magellanic Clouds, we estimated the photometric metallicities of their Cepheid populations [17]. We were interested if the difficulty of evolving low-luminosity (low-mass, mostly first overtone) stars into the instability strip at high/medium metallicities may indeed come from the lower metallicity they have in comparison to their cousins pulsating in the fundamental mode (Cordier et al. 2003). From the above study we got supporting evidence that this may indeed be the case.

We reviewed the outstanding, so far unsolved problem of Blazhko phenomenon in [18]. Together with the summary of the basic inadequacies of the currently available explanations, we also presented toy hydrodynamical (numerical) models based on artificially enhanced opacities in the deep envelopes (caused by a presumed heavy element surplus accreated in the earlier history of RR Lyrae evolution). Without vindicating that this is a viable explanation of the Blazhko effect, I note that in the proximity of the 2:1 resonance between the fundamental mode and second overtone these models are indeed capable of showing amplitude modulation, in some respects resembling to the observed Blazhko modulation.

We investigated the problem of deriving the basic physical parameters of the double-mode RR Lyrae (RRd) stars by using only their observed periods through the application of linear pulsation and evolutionary models. In [9] we took the particular case of the field star BS Com, that has been observed as part of the program aimed at the photometric monitoring of RR Lyrae stars.[5] We compared the observed colors and the metallicities available in the literature and we found good agreement with the derived purely theoretical values. In a subsequent publication [10] we used a representative sample of RRd stars from the LMC to derive a theoretical period-luminosity-color (PLC) relation. When compared with the one obtained through the Baade-Wesselink analysis of Galactic field fundamental more RR Lyrae stars, we obtained the result shown in Fig. 7. The overall agreement is good, although there is a significant difference between the empirical and the theoretical (RRd) slopes. We suspect that this difference can be accounted for either by the underestimation of the true slope by the empirical method (since it is based on globular clusters with supposedly homogeneous chemical compositions), or by the different slice of parameter space occupied by the RRd stars (please note that the PLC relation depends on the mass spectrum).

Based on the photometric observations made by the Schmidt telescope at the Konkoly Observatory, we performed a variability survey of the globular cluster M53, in particular emphasis on the applicability of TFA in the case of small sample size and on the properties of the RR Lyrae stars [11]. Example for the former will be given in the next section, whereas for the latter we highlight the results concerning the demonstration of the existence of a unified PLC relation followed by the fundamental and first overtone RR Lyrae stars and the metallicity difference derived between the giant and the RR Lyrae population of the cluster. We show this latter result in Fig. 8. We suspect

[5] http://www.konkoly.hu/24/index.html

that the most probable reason of the difference is lack of low-metallicity stars in the calibrating sample of Jurcsik & Kovács (1996), on which the metallicity estimates of the RRab stars are based. Nevertheless, a direct spectroscopic investigation of both the red giants and the RR Lyrae stars would be necessary to offer a more straightforward answer on this puzzling result.

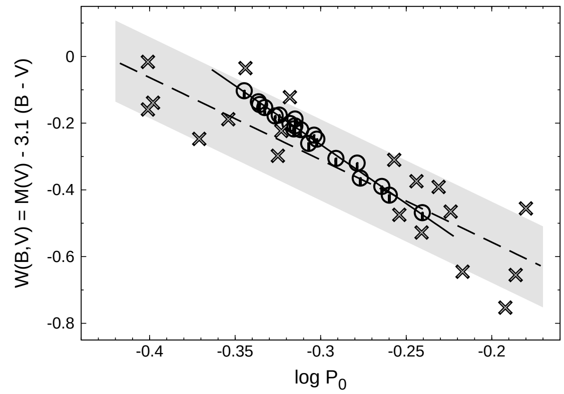

Fig. 7. Period-luminosity-color (PLC) relation for the Baade-Wesselink (BW) stars (crosses, see Kovács 2003) and for the RRd sample from the LMC. The 3σ range of the BW sample is shown for reference. Dashed line corresponding to the slope of the empirical relation derived by Kovács & Walker (2001). Solid line is the result of a regression to the RRd PLC relation.

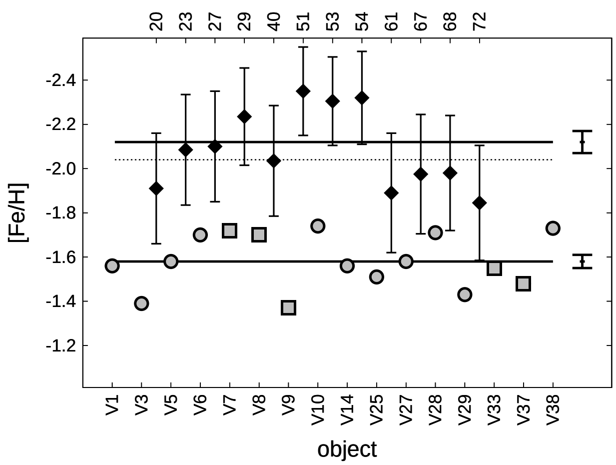

Fig. 8. Photometric metallicities obtained for the red giant (diamonds) and for the RR Lyrae population (circles, our data; squares, Kopacki's, 2000 data) of M53. Continuous lines are for the averages, dashed line is for the Zinn and West value. The error bars show the 1σ errors of the averages.

3.2 Data analysis

We implemented the method of template Fourier fitting to compute the Fourier decompositions of sparsely sampled and/or noisy light curves of RRab stars [16]. The method has been shown to be a useful means to yield better estimates for quantities, such as [Fe/H] and average brightness, derived from the light curves.

We dealt with the applicability of TFA in four papers. In [13] we showed that the false alarm probability of transit detection can be very significantly decreased by using multiple templates (i.e., various sets of templates). The case of Fourier signals was discussed in [15], where we presented a one step formalism to reconstruct the signals in the presence of systematics, assuming that the frequencies are known from an earlier analysis. We note that for transit signals this reconstruction step is iterative. In [11] and [27] we tested TFA on data sets containing sparsely sampled time series with moderate/few data points. The method has been proved to be successful both on the MACHO sub-sample from the LMC [27] and also on the data set of M53, containing even fewer data points. The detection of a variable dominated by systematics is shown in Fig. 9.

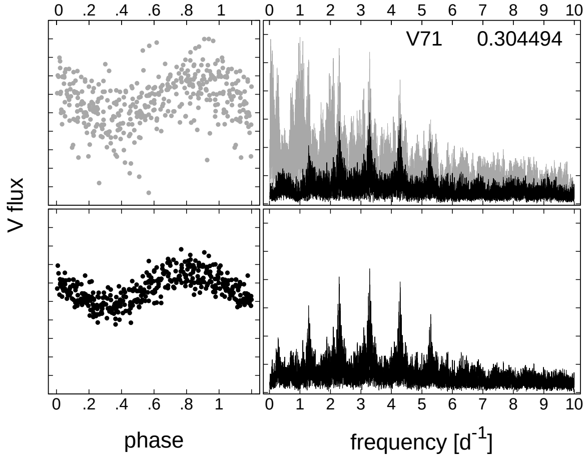

Fig. 9. Detection of the first overtone RR Lyrae star V71 in the globular cluster M53. The light curve contains 340 data points spread over 430 days in two seasons separated by nearly one year. Original folded light curve (with the period obtained from the TFA-filtered data) is shown in the upper left panel, whereas the TFA-reconstructed light curve is plotted at the lower left. Fourier frequency spectra of the TFA-d time series are shown by the black-shaded spectra in the right panels (the upper one was obtained from the TFA-d signal with the assumption of dominating systematics – the so called "zero signal assumption", whereas the lower one is the spectrum computed from the reconstructed signal – that uses a complete signal model). Gray-shaded spectrum was computed from the original (non-TFA filtered data).

4. Scientific impact and related activities

We have published 28 papers (including some conference proceedings) acknowledging the support of this grant. As of 2010.02.25, we received 245 independent citations on the above publications, with the first discovery (HAT-P-1) leading the list by 67 citations (followed by HAT-P-2 by 42 and the rest by less than 20 per object and citations to other, non-extrasolar planet papers).

We gave talks at several international conferences (GK: 2 contributed and 1 invited; GB: 3 contributed and 3 invited; István Dékány [joined to the grant as participant from mid 2009]: 1 contributed). The discovery of some of the planets stimulated fair amount of public interest, e.g.,

HAT-P-1 (New York Times, BBC):
http://www.nytimes.com/2006/09/15/science/space/15planet.html?_r=1&pagewanted=print
http://news.bbc.co.uk/2/hi/sci/tech/5346998.stm

HAT-P-7 (Astronomy Now, UK Magazine):
http://www.astronomynow.com/news/n0908/06kepler/

HAT-P-11 (National Geographic, MSNBC)
http://news.nationalgeographic.com/news/2009/01/090122-super-neptune-photo.html
http://cosmiclog.msnbc.msn.com/archive/2009/01/21/1755242.aspx

HAT-P-13 (Nepszabadsag):
http://beta.nol.hu/tud-tech/magyarok_exobolygorendszert_talaltak

In hardware-related issues we note that two servicing trips were made to the WHAT telescope by István Papp (HAT engineer) and *kohat5*, a multi-Tb-capacity computer was installed in 2007 at Konkoly Observatory.

We employed graduate students Brigitta Sipőcz and Gábor Kovács in various periods of few months for working on data handling, reduction and software-related problems. Judit Szulágyi was a BSc student between 2006-2009, István Dékány is defending his PhD Thesis by the middle of 2010. Both students were supervised by GK. András Pál defended his PhD in 2009 under the supervision of GB.

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