Tools for discovering and characterizing extrasolar planets

Theses of the PhD Dissertation

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1 Introduction

In the last two decades systematic searches for extrasolar planets resulted in several hundreds of discoveries. The diversity of the known planetary systems is quite noteworthy. Planets orbit their parent stars with periods of a day up to several years, there are numerous systems with multiple planets and planets are also known to exist around pulsars[1]. In fortunate cases when the planetary orbit is nearly perpendicular to the plane of sky, the observed stellar brightness drops a small amount when the planet transits the disk of the host star. Such transit events can be observed by photometric methods. For instance, a hypothetical planet with the size of Jupiter would yield a flux decrease around 1% assuming a host star similar to our Sun. Transiting extrasolar planets are the only group among the extrasolar planets whose basic physical parameters, such as mass and radius can be determined without any ambiguity. Therefore, these planets provide a great opportunity to determine other properties, such as the characteristics of planetary interiors or atmospheres, or to estimate the composition of these atmospheres by performing further spectro-photometric measurements during transits. Recently, photometric surveys have become the most prominent observation techniques for detecting planetary transits and these surveys yielded several dozens of discoveries, approximately 90% of the currently known 58 transiting extrasolar planets.

2 Scientific goals

Transit events have a relatively short duration compared to the orbital period of the planet, therefore stars should be continuously observed for several months in order to obtain a significant detection, even for short periods of a few days. The discovery rate significantly increases if brighnesses are monitored for numerous stars. Indeed, the most successful dedicated surveys utilize telescopes with large field-of-view and monitor several tens or hundreds of thousands stars simultaneously. These wide-field surveys intended to search for periodic photometric transits by extrasolar planets yield massive amount of raw data in the form of astronomical images. In contrast of the previously wide-spread reduction methods, wide-field surveys induce rather new related problems due to the large distrotion, crowded, sharp and undersampled stellar profiles and the enormous amount of individual sources of interest. Since such a large amount of special data cannot be efficiently and consistently processed by the available existing

[1] See e.g. `http://exoplanet.eu` for up-to date information.

software solutions, I started developing a new package in order to overcome the related problems. The development of this package has been related to the Hungarian-made Automated Telescope Network (HATNet) project[2], one of the most successful initiatives dedicated to searching for transiting extrasolar planets. The aims of my work were both implementing the algorithms related to the complete photometric reduction in a form of a standalone software package, as well as applying these programs in the analysis of the HATNet data. Of course, both the confirmation of planetary candidates and the characterization of known objects require other types of technologies such as spectroscopy, radial velocity measurements and stellar evolution modelling. In order to perform a consistent determination of the planetary, orbital and stellar parameters of transiting exoplanetary systems, my work also focused on including these additional types of measurements in the data analysis.

3 Methods

To perform a homogeneous reduction on the raw data gathered by the HATNet telescopes, several sophisticated algorithms have to be applied subsequently and the implementation of these algorithms must ensure the self-consistent data manipulation (although this latter condition seems to be trivial, self-consistent processing is not guaranteed at all if various software packages from different origins are involved in the reduction pipeline). Moreover, due to the huge amount of raw images, the implementation should be computationally efficient. Therefore, I designed the whole reduction package to work under various UNIX-like operating systems (including and primarily focusing on GNU/Linux systems). The planetary nature of objects detected with transit photometry needs to be confirmed involving data other than photometry. Although the reduction package is not capable to deal with raw spectroscopic measurements, the regression utilities can be used to transparently incorporate such types of data in the analysis.

Additionally, the photometric reduction code is intended to work on data obtained by other kind of facilities, such as the 48" telescope at the Fred Lawrence Whipple Observatory or the Schmidt telescope at the Piszkéstető Mountain Station. These instruments have also been involved in the HATNet project, used to perform follow-up photometry of planetary candidate host stars.

In summary, the obtained photometric, spectroscopic and radial velocity data com-

[2]`http://hatnet.hu`

plemented with modelling of stellar evolution yielded a consistent parameter determination for several planets either discovered or observed by the HATNet project.

4 Theses

Algorithms and software environment

(1) Involving various techniques, I developed a standalone software package (FI/FIHAT) intended to perform efficient and complete photometric reduction of astronomical images. In particular, the package is suitable for:

- calibration of series of individual scientific frames, using standard methods (overscan correction, bias, dark, flat), as well as additional masks which can be added in order to exclude faulty or saturated pixels from further processing;
- source identification and characterization based on a purely topological algorithm, suitable to perform well on undersampled and crowded images;
- cross-matching of coordinate lists and derivation of astrometric solutions, taking into account higher order distortions;
- convolution and image subtraction which is essential in the cases of images with extremely crowded stellar profiles;
- instrumental photometry, on both normal and subtracted images; and
- massive data transposition and creation of light curves.

The details of the algorithms used in the derivation of the astrometric solutions have been published by Pál & Bakos (2006).

(2) I have continued the development of a generic regression tool, `lfit`, which features several independent algorithms for data analysis. This program implements the light curve de-trending algorithm of EPD, that was used extensively in the reduction of HATNet data (see e.g. Bakos et al. 2007c or Pál et al. 2008a). I have created an improved version of the Markov Chain (MCMC) Monte-Carlo algorithm that utilizes parametric derivatives of the model function as well as other minimization methods (such as downhill simplex) to be a faster and more reliable alternative for the classic MCMC method. This algorithm has also been implemented in the framework of `lfit` with numerous additional sanity checks for chain convergence. I have used this tool during the data reduction of HAT-P-11b, the smallest planet discovered by ground-based transit surveys (Bakos et al. 2009). In order to have consistent results, in this analysis the de-trending algorithms (EPD, TFA) and light curve modelling have been performed simultaneously.

(3) Many of the regression and data analysis algorithms require the knowledge of partial derivatives of functions involved in the modelling. I have calculated the parametric derivatives of the most widely used transit light curve model functions (Pál 2008) and implemented in the previously discussed `lfit` program.

HATNet discoveries

(4) My own programs found in the package FI/FIHAT played a key role in the discovery or the characterization of all of the transiting planets discovered by the HATNet project (Bakos et al. 2007a, Bakos et al. 2007b, Kovács et al. 2007, Bakos et al. 2007c, Noyes et al. 2008, Pál et al. 2008a, Latham et al. 2008, Shporer et al. 2008, Bakos et al. 2008, Bakos et al. 2009). Moreover, the astrometric and photometric measurements presented in various follow-up analyses (e.g. Bakos et al. 2006a, Bakos et al. 2006b, Holman et al. 2007, Winn et al. 2007) and independent discoveries (Pál et al. 2008b) have also been obtained with the help of these programs.

(5) As presented by Pál et al. (2008b), I demonstrated how the stellar evolution modelling has to be incorporated in the procedure of planetary system characterization in order to yield a consistent solution in the case of transiting extrasolar planets. This type of analysis has been used frequently in many recent discoveries and follow-up observations (Pál et al. 2008a, Latham et al. 2008, Bakos et al. 2008, Bakos et al. 2009, Pál et al. 2008c, Pál et al. 2009).

(6) I analyzed the photometric and radial velocity data from the planetary system HAT-P-7(b) in order to obtain the stellar, orbital and planetary parameters (Pál et al. 2008a). In addition, the images recorded by HATNet have been reduced involving the method of image subtraction in order to present a detailed comparison between various photometric methods and have a more precise analysis of the planetary system. This new reduction method has shown that photometry based on image subtraction can significantly increase the quality of light curves.

Follow-up observations

(7) Employing various reduction techniques (presented in Pál & Bakos 2006, Pál et al. 2008a, Pál, Bakos, Noyes & Torres 2008), I refined the parameters of the planetary system HAT-P-2b (Pál et al. 2009). This refined analysis was based on numerous additional photometric and radial velocity measurements, and resulted in stellar parameters that are consistent with independent measurements such as the absolute magnitude (derived from the parallax of the system). I have also compared the system parameters with recent models of planetary interiors. In order to model radial velocity measurements for eccentric planetary orbits, I developed a new formalism for the solution of Kepler's Problem which involves a few basic functions with small number of parameters which are shown to behave analytically (Pál 2009). Due to the analytic property of these functions, the radial velocity variations in case of an eccentric orbit can be quantified easily.

5 Conclusions

In this PhD thesis I presented a new software package designed for performing photometric data reductions on a massive amount of astronomical images. Existing software solutions do not provide a consistent framework for the reduction of images acquired by wide-field and undersampled instrumentation. During the development of the related algorithms and the implementation, I focused on the issues related to these problems in order to have a homogeneous reduction environment, from the calibration up to the final light curve generation and analysis. This new package has been successfully applied in the processing of images of the Hungarian-made Automated Telescope Network and led to the discovery and confirmation of almost a dozen of transiting extrasolar planets.

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