New Astronomy 15 (2010) 297–301

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Exoplanet Transit Database. Reduction and processing of the photometric data of exoplanet transits

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A R T I C L E   I N F O

Article history:
Received 29 June 2009
Received in revised form 28 August 2009
Accepted 1 September 2009
Available online 6 September 2009
Communicated by W. Soon

PACS:
95.80.+p
97.82.−j
97.82.Cp

Keywords:
Exoplanets
Planetary systems
Techniques: photometric
Database

A B S T R A C T

We demonstrate the newly developed resource for exoplanet researchers – The Exoplanet Transit Database. This database is designed to be a web application and it is open for any exoplanet observer. It came on-line in September 2008. The ETD consists of three individual sections. One serves for predictions of the transits, the second one for processing and uploading new data from the observers. We use a simple analytical model of the transit to calculate the central time of transit, its duration and the depth of the transit. These values are then plotted into the observed–computed diagrams (O–C), that represent the last part of the application.

1. Introduction

Research on extrasolar planets is currently one of the most exciting fields in astrophysics. The speculations on the existence of planets orbiting other solar-type stars ended 14 years ago. In 1995 the discovery of the first extrasolar planet orbiting a solar-type star – the well-known 51 Peg b, was made by Mayor and Queloz (1995). Since then, the number of known planets has been growing quickly. Currently, more than 370 such bodies are known.[1]

If a planetary system happens to be oriented in the space so that the orbital plane is close to the line-of-sight to the observer, a planet periodically passes in front of the stellar disk. Photometric observation of the transit can then be used to derive the orbital and physical parameters of the planet (e.g., Southworth, 2008 or Torres et al., 2008). For a review of properties that have been measured, or that might be measured in the future through precise observations of transiting planets, see Winn (2008). At the half of the year 2009, more than 60 planets with this special orientation were known.

There are many amateur astronomers all over the world that achieved photometric accuracy around the units of percent, which is necessary for quality observing of the exoplanet transit. Unfortunately, up to present day, no exoplanet light curves' database was available that would accept data from both professionals as well as from amateurs. Amateur observers are not constrained by telescope scheduling and often have unlimited access to their instrument which enables them to gather data over a long period.

Huge quantity of observations is the key to the search for other planets in already known systems. It is important to monitor possible periodical changes in O–C plots of the planets because as Holman and Murray (2005) demonstrated in their theoretical work, short-term changes of the time of the transit can be caused by the presence of other exoplanets or moons in the system, see also Agol et al. (2005) and Kipping (2009). On the other hand, potential long-term changes in the duration of the transit may be

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[1] See the list http://www.exoplanet.eu.

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doi:10.1016/j.newast.2009.09.001

the consequence of orbital precession of exoplanets as Miralda-Escudé (2002) showed in his theoretical work. To perform such effective studies, we need a database which includes all available data divided into groups according to their quality.

2. Why ETD

The Exoplanet Transit Database[2] (ETD) came on-line in September 2008 as a project of the Variable Star and Exoplanet Section of the Czech Astronomical Society. The ETD includes all known transiting planets that have published ephemerides.

We have created on-line ETD portal to supply observers with such useful information like transit predictions, transit timing variation (TTV), variation of depth and duration with availability to draw user observation to the plot.

Before the ETD, only two other transit databases were available. The Amateur Exoplanet Archive[3] (AXA), lead by Bruce Gary, and the NASA/IPAC/NExScI Star and Exoplanet Database[4] (NStED) (von Braun et al., 2008). AXA strictly accepts data only from amateurs. Unfortunately, the quality of light curves is very diverse. In spite of this fact, all of the available light curves have the same priority grading. On the other hand NStED contains only the light curves that have been already published (in the future some amateur light curves from AXA should be also accepted into the NStED and the AXA should expire).

The main goal of the ETD is to gather all available light curves from professional and also amateur astronomers (after 1 year of the existence of the database, more than 1000 such records are available). We are searching for new publications on several open archives to gather all available light curves. We also take over data from the NStED, AXA and from our project TRESCA.[5] It is also possible to upload data into the database directly using a web-form or it can be added to the database by the administrators. All available data are on-line plotted into graphs where we make the provision for the quality of the light curve. All graphs (like TTV) can be easily downloaded from the database. It is also possible to download light curves from the TRESCA observers and from amateur observers directly from the database.

While collecting published data to ETD, we accentuate to have fully referenced its source. Each transit observation we store full reference with URL pointing to the paper or web-page where data were found. When we take over the whole light curve we display it only with reference to source of the data there is no mention of ETD in the picture.

3. Parts of the ETD

The ETD is composed from three sections. The first one – Transit prediction – serves for prediction of the transits. The second one – Model-fit your data – is a web-form for accepting and processing new data. The last section – O–C plots – contains the observed – computed diagrams of the central times of transits, depths and the transit durations that are generated on-line from the database.

3.1. Transit prediction

This section of the ETD contains 1 month prediction of observable transits (the starting day is the date 2 days before current date) and also the prediction for the next 365 days for selected exoplanet. Any observer can find here the time of the transit start/center/end, duration and the depth of each transit for any place in the world. Furthermore the altitude and the cardinal point of the object in the sky are displayed for the first contact, mid-transit time and the last contact. In the 1 year prediction window you can also see the finding chart[6] ($15' \times 15'$).

3.2. Model-fit your data

This section describes an user-friendly web-form for uploading and processing the light curves into the database. To model-fit the transit we assume that the observations consist of N relative magnitudes m_i taken at times t_i ($i = 1, 2 \ldots, N$) and the photometry software provided measurement errors σ_i computed most likely from Poisson statistics and read-out noise. We model the dataset by a function

$$m(t_i) = A - 2.5 \log F(z[t_i, t_0, D, b], p, c_1) + B(t_i - t_{\text{mean}}) + C(t_i - t_{\text{mean}})^2, \quad (1)$$

where $F(z, p, c_1)$ is a relative flux from the star due to the transiting planet. We assume that the planet and the star are dark and limb-darkened disks, respectively, with radius ratio $p = R_P/R_*$ and that the planet is much smaller than the star, $p \lesssim 0.2$. The projected relative separation of the planet from the star is z. Limb darkening of the star is modeled by the linear law with the coefficient c_1. We employ the occultsmall routine of Mandel and Agol (2002) as our $F(z, p, c_1)$. We checked that the small planet approximation, $p \lesssim 0.2$, does not produce significant differences from the full model (at least for the typical values of p and having in the mind the typical quality of the photometry) and is much faster to compute, which is the most important factor for on-line processing.

We model the planet trajectory as a straight line over the stellar disk with impact parameter $b = a \cos I/R_*$, where a is a semi-major axis and I is the orbit inclination. The mid-transit occurs at t_0 and the whole transit lasts D. Based on these assumptions we can compute $z[t_i, t_0, D, b]$ for every t_i.

Variable A in the Eq. (1) descibes the zero-point shift of the magnitudes, while B and C describe systematic trends in the data. Linear and quadratic terms are computed with respect to the mean time of observations $t_{\text{mean}} = \sum t_i/N$ to suppress numeric errors. We do not employ any explicit correction for air-mass curvature as we think a generic second-degree polynomial is sufficient in most cases.

We used the Levenberg–Marquardt non-linear least squares fitting algorithm from Press et al. (1992), procedure mrqmin. The algorithm requires initial values of parameters and partial derivatives of the fitted function. We take the initial values from literature (except for c_1, see below). We compute all partial derivatives of the Eq. (1) analytically, except for $\partial F/\partial z$, $\partial F/\partial p$ and $\partial F/\partial c_1$ which were computed numerically using Ridders' method (procedure dfridr of Press et al. (1992)).

The search for the optimal parameters is done by iterating the fitting procedure until the $\Delta\chi^2$ (between fits) does not change significantly. Usually, with good initial values, about ten iterations are sufficient. Then the error bars σ_i are re-scaled to make the final $\chi^2 = N - g$, where g is a number of free parameters, and we re-run the fitting procedure to obtain final errors of the parameters. Original photometric errors are usually underestimated and this procedure yields more reasonable errors of the output parameters.

In the optimal circumstances, one would consider all variables in Eq. (1), namely A, B, C, t_0, D, b, p and c_1 free parameters. However, these parameters are correlated to some extent and noisy photometry from a small amateur telescopes does not permit recovery of all of them. We need to fit the zero-point shift A and in most cases

[2] http://var2.astro.cz/ETD.
[3] http://brucegary.net/AXA/x.htm.
[4] http://nsted.ipac.caltech.edu.
[5] http://var2.astro.cz/EN/tresca.
[6] Downloaded from the http://archive.stsci.edu/dss/index.html.