The improved code *TAC maker* for modeling of planet transits

D. Kjurkchieva[1], D. Dimitrov[2], A. Vladev[1]
[1] Department of Physics, University of Shumen, 72 Universitetska Str., 9712 Shumen
[2] Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72 Tsarigradsko shose Blvd., 1784 Sofia
d.kyurkchieva@shu-bg.net

(Submitted on 30.05.2014. Accepted on 18.06.2014.)

Abstract. We present improvements of the code *TAC-maker* for modeling of planet transits. While the initial version of the code calculated synthetic transits for certain values of the input parameters, the new version *TAC-maker* 1.1.0 gives a possibility to obtain simultaneously numerous synthetic transits corresponding to chosen ranges of values for each fitted parameter. The most valuable property of the improved version of the code is the ability to obtain the global minimum of χ^2 in the multidimensional parametric space and to estimate the errors of the searched parameters.

Key words: techniques – numerical calculations: planetary system – stars: photometric – eclipses – stars: transits – stars:

Introduction

The scales of the global parameters of the configurations containing transiting extrasolar planets (TEPs) are different from those of eclipsing systems (EBs) of two stars. The main geometric difference is that the radii of the components of EBs are comparable while the radii of TEPs are negligible compared to the radii of their host stars. As a result almost all old, well known codes (excluding JKTEBOP (Southworth, Maxted & Smalley 2004a,b, Southworth 2008)) for modeling of EBs fail in the reproducing of planet transits (due to numerical errors around the transit center). That is why new approaches and codes for modeling of TEPs had to be designed at the beginning of new millennium, the era of numerous exoplanet discoveries.

Several solutions of the direct problem for planet transits were proposed (Mandel & Agol 2002; Seager & Mallen-Ornelas 2003; Gimenez 2006; Kipping 2010). They were based on several simplifications: the planet is an opaque, moving circle on the stellar disk; the planet path on the stellar disk is straight line; the stellar limb-darkening law is quadratic or nonlinear. All proposed solutions contain different types of special functions. The corresponding codes for generation of synthetic transits calculate numerically the values of the special functions. These codes were widely used for modeling of observed transits.

Recently we proposed a new approach for solution of the direct problem of planet transits that is based on transformation of the double integrals to single ones (Kjurkchieva & Dimitrov 2012, Kjurkchieva et al. 2013). It does not use any simplifications and is capable to take into account arbitrary stellar limb-darkening law and planet temperature. The corresponding code *TAC-maker* (**T**ransit **A**nalytical **C**urve) calculates synthetic transits by numerical calculations of single integrals. This paper presents the new, improved version of the code designed for successful modeling of observed planet transits.

***TAC-maker*: initial version**

The code *TAC-maker* was written in *Python* with a graphical interface.

TAC-maker calculates synthetic transits for the following input parameters: radius of the planet orbit a; radius of the host star R_s, radius of the planet R_p; orbital inclination i; temperature of the star T_s; temperature of the planet T_p; coefficients of the stellar limb-darkening u_j. The user may choose also limb-darkening law between four widely-used types. The result of the running of the code – the synthetic transit – is a two-dimensional data file (phase φ, flux f_s) and a plot of the calculated transit.

The initial version *TAC-maker* 1.0.0 gave a possibility for "manual" modeling of observed planet transits. For this aim a special tab allows to download observational data. Then the running of the code results in four outputs: 3-dimensional data file (phase φ, synthetic flux f_s, observed flux f_o); window with plot of the synthetic transit and the observational data; window with plot of the residuals for each observational phase; field with the value of χ^2. By manually varying of the input parameters the user may search for a minimum of χ^2 and thus model the observed transit (method of trials and errors). The steps of varying of the fitted parameters may be adopted as some estimations of their precisions.

However, there is not a certainty that the found minimum of χ^2 in this way is the searched global minimum in the multidimensional parametric space. In order to overcome this problem, to fast the modeling of the planet transits and to obtain objective errors of the searched parameters we undertook development of our code.

Improved version of *TAC-maker*

We changed the design of the code to include its new abilities. The main screen is separated into several sections (Fig. 1).

Section *Parameters* serves to choose the parameters of the exoplanet system. The main fields of this section are the same as those of the old version: (a) "Semi-major axis" to set the orbital radius of the transiting planet in AU; (b) "Stellar radius" to choose the radius of the star in AU or R_{Jup} (the conversion between them is automatical); (c) "Planet radius" to set the radius of the planet in AU or R_{Jup} (the conversion between them is automatical); (d) "Stellar temperature" to choose the temperature of the star; (e) "Planet temperature" to choose the temperature of the planet; (f) "Inclination" to set the orbital inclination in degrees; (g) "Darkening law" to choose the stellar limb-darkening law between four widely-used types; (h) "Darkening coefficient 1,2" to set the corresponding limb-darkening coefficients (for instance, from Claret (2004)).

The improvements of the new version of *TAC-maker* in Section *Parameters* are the additional "R" buttons on the left of each input field. They allow to choose wanted range of values of the searched parameter. The click on the "R" button opens a new small window with three fields: "From" for the minimum value of the range, "To" for the maximum value of the range and "By" for the step. In fact, the ratio "(maximum value – minimum value)/step" gives the number k of the values for a given parameter.

If the user wants to hold some parameter fixed he/she has not to press the "R" button but only to write the fixed value in its input field. The visual discrimination of the user choice is provided by color background: the "R" buttons of the parameters which values are fixed are white while those of the parameters with chosen ranges of values are blue (Fig. 1).

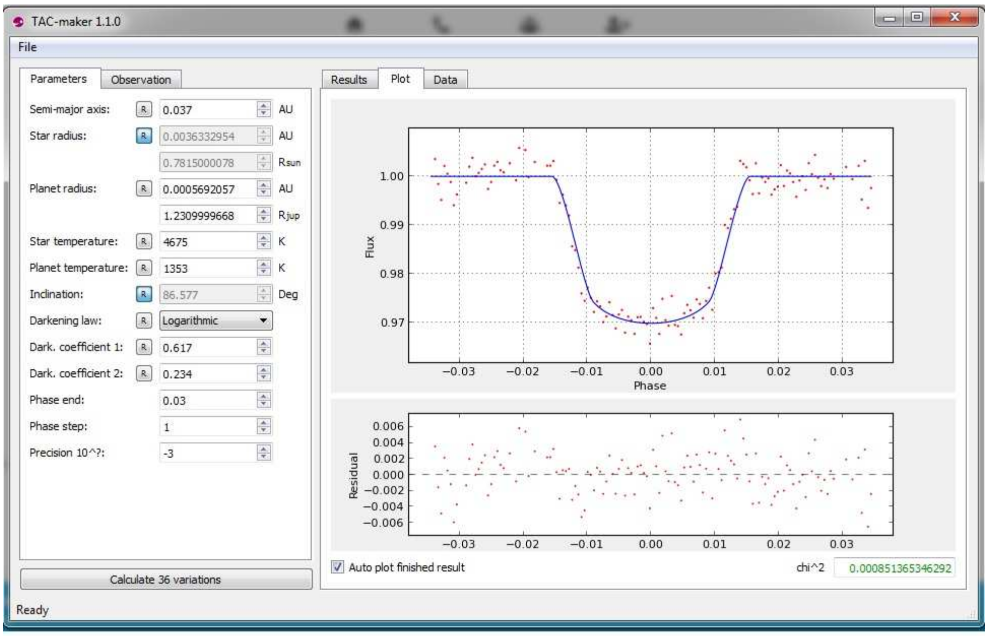

Fig. 1. The screen of *TAC-maker* 1.1.0

After filling-in all parameter fields one may run the calculations by the button "Calculate" on the left bottom of the screen. If the user has chosen the range of values for at least one parameter then the label of the button "Calculate" automatically becomes "Calculate N variations" where $N = k_1.k_2...k_s$ is the total number of all combinations of the parameter values (s is the number of the fitted parameters). Thus, *TAC-maker* 1.1.0 produces N synthetic solutions by one clicking of the button "Calculate".

Section *Observation* serves for loading of the file with observational data by the button "Browse". This file may contain different quantities: the first column "phase" or "HJD" and the second column "flux" or "magnitude". The user may convert "HJD" to "phase" by clicking the button "Convert HJD to phases" and filling the appearing fields T_0 (HJD of the transit center) and P (orbital period of the planet in days). The user may convert "magnitude" data to "flux" by the button "Convert magnitude to flux". It opens a new field that requires the filling of the (mean) out-of-transit magnitude. After this preliminary procedure the button "Redraw" provides a plot of the imported data (Fig. 2).

Section *Results* had to be wholly reworked because the initial version of the code contained one solution (for fixed parameter values) while the output of the new version presents a set of numerous solutions. It appears as a table "Results" which columns are the fitted parameters while the rows contain all combinations of the parameter values (Fig. 3). If observational data are preliminary loaded table "Results" contains additional column with the calculated values of χ^2 for each synthetic transit.

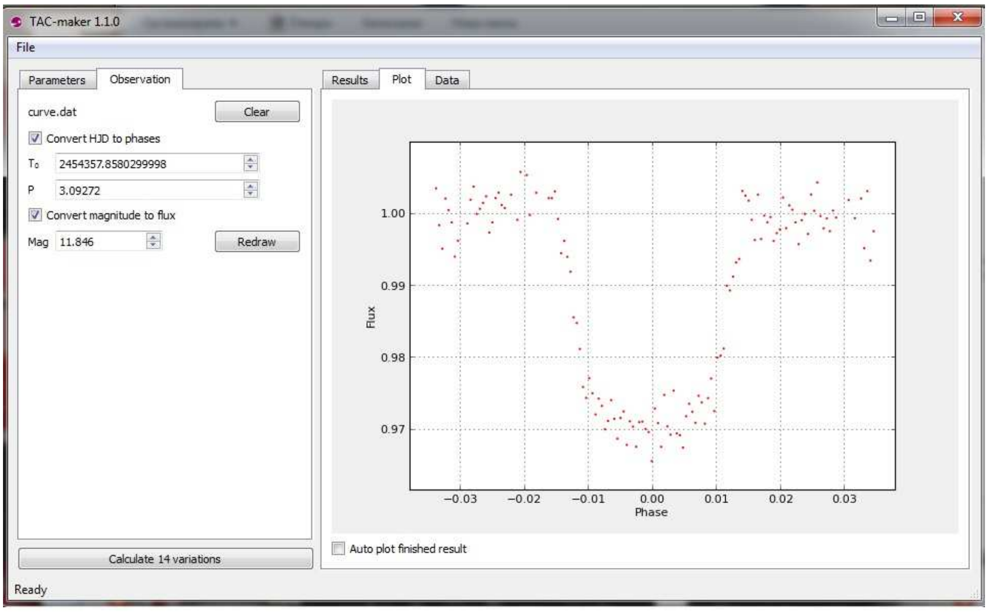

Fig. 2. Section *Observation*

Each solution can be seen if the corresponding row is active by two means:

(a) choosing tab "Data" as a data file with four columns (Fig. 4): Phase; Synthetic (calculated flux values); Observation (imported flux values); Delta (residuals);

(b) choosing tab "Plot" as two figures (Fig. 1, right): the upper panel presents the synthetic transit as a blue line and the imported data as red dots while the lower panel shows their residuals (differences between the calculated and observed fluxes) for each observed phase as well as the χ^2 value for the current solution.

There is also a possibility to see each new-calculated transit during the calculation procedure by activation of the button "Auto plot finished result" at the bottom of the "Plot" tab (Fig. 1). Then a plot with the current synthetic transit and χ^2 value appears automatically when its calculations are finished. The color of the χ^2 value changes from red to green for the local minima. The option "Auto plot finished result" can be unchecked to speed-up the calculations.

The content of table "Results" can be sorted by columns that is very convenient for the user (especially for χ^2). One may hide/show any column of this table by right-clicking of its header. Moreover, there is a possibility to delete or reload chosen solution from the table by right-clicking on its row. The button "Delete all" (at the right bottom of section "Results") deletes all results simultaneously.

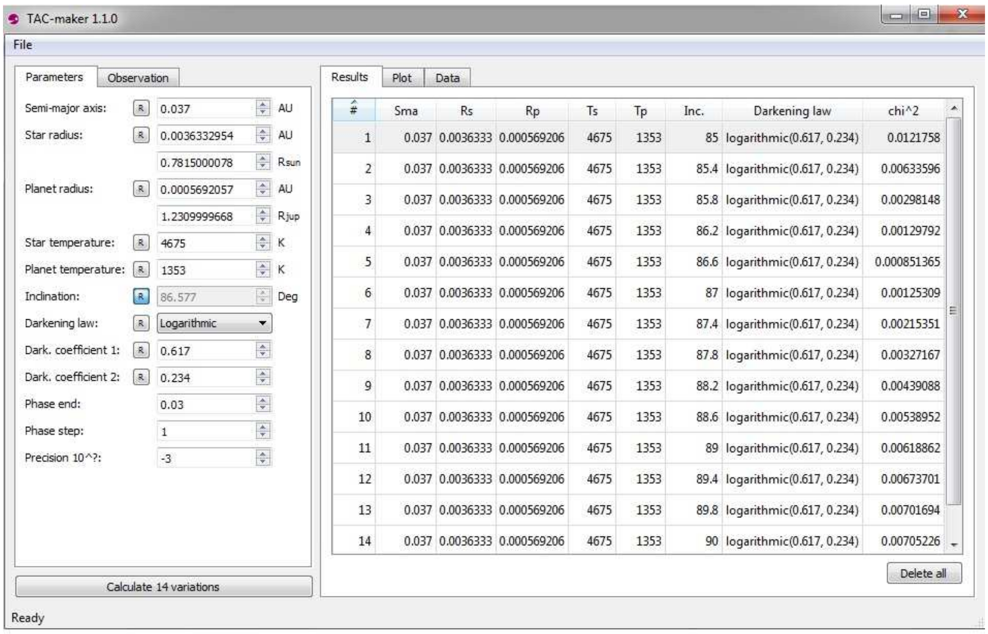

Fig. 3. Section *Results*

The calculations from each subsequent operation "Calculate" in the same session are automatically accumulated in Table "Results". The previous solutions might be deleted by button "Delete all" before new "Calculate".

The file from tab "Data" can be exported for further use by the button "Export..." (on the right bottom of the field "Data", Fig. 4).

Section "File" (on the left top of the screen) serves for opening and saving of the solutions. One can use "data/" folder to store the files with observational data (for instance "name.dat") and the calculated transits (for instance "wasp10.ini"). They can be loaded from menu "File → Open...".

The files from the last user session are automatically saved when the user exits the code. The next run of the program loads automatically the values of section "Parameters" from the last session.

TAC-maker 1.1.0 and the inverse problem solution

The previous section demonstrates one of the advantages of *TAC-maker* 1.1.0: the possibility to obtain a set of synthetic transits by one running of the code. This allows considerable saving of user and computer time for modeling of observed transit by trials and errors.

However, the most valuable property of the new version is the ability to obtain the right solution to the inverse problem. The procedure consists of several "manual" stages but the codes for modeling of eclipsing stars also work without automate iterations.

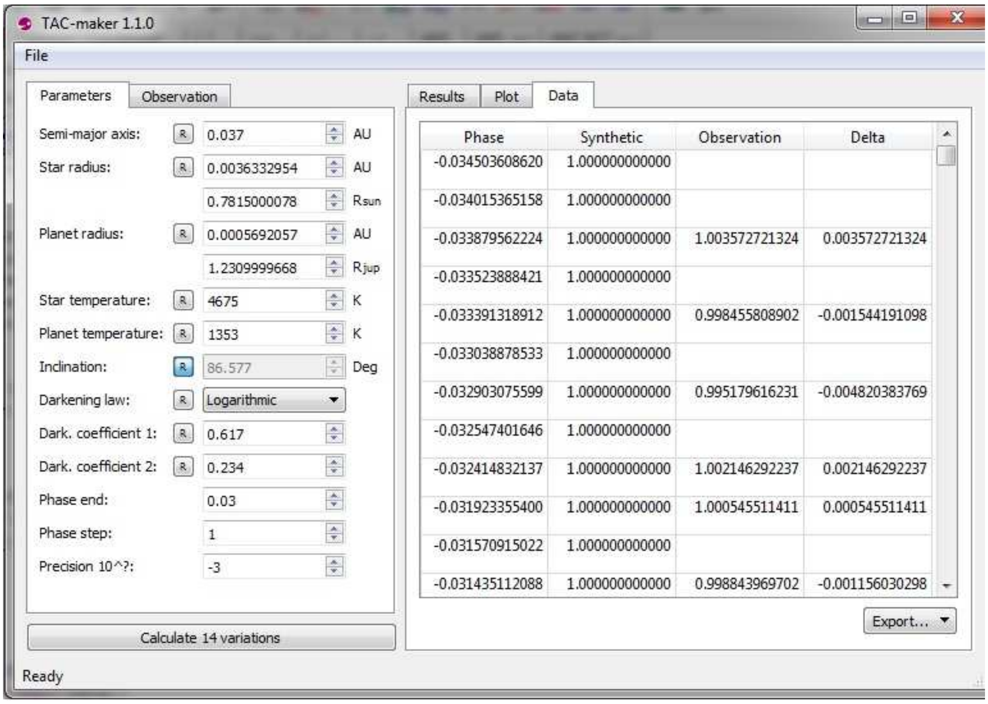

Fig. 4. Section *Data*

At first the user searches for a rough solution. For this purpose the ranges of all input parameters should be set large (but not arbitrary). The obtained synthetic transit with minimum χ^2 value may be considered as an initial solution of the inverse problem.

Further the user may choose smaller ranges of the fitted parameters around the initial solution and smaller steps. The second run of the code will give the second approximation of the solution. After several such steps the user reaches to value of χ^2 that is of order of the observational precision and hence, next improvements of the data modeling are meaningless. This is the final solution of the inverse problem.

The error of a given fitted parameter may be estimated by building diagram parameter values vs. corresponding χ^2 (using columns of table "Results"). The fitting of these data with polynomial allows to obtain the precision of the searched parameter.

To save computational time one should keep low value of the parameter "Precision $10^?$" (that determines the precision of integration) during the procedure of a raw solution of the inverse problem. Moreover, in case of great number of observational points (for instance data from *Kepler* mission) one should set "Phase step"=1. Then the code calculates synthetic fluxes only for the imported (observational) phases that reduces the time for calculations.

Conclusions

The increasing number of discoveries of planet candidates recently and the ever increasing precision of the observations require improvement of the methods for extraction of the parameters of the planetary systems from the observational data. The present paper is a step in this direction.

The initial version of our code *TAC-maker* calculated transits for certain values of the planet configurations, while the new improved version, *TAC-maker* 1.1.0, generates numerous synthetic transits corresponding to ranges of values for each input parameter.

Important advantages of the improved version of the code are the fast modeling of observed transits and estimation of the errors of the fitted parameters. But its most valuable property is the ability to find the global minimum of χ^2 in the multidimensional parametric space, i.e. to obtain the right solution to the inverse problem.

The new version of the code *TAC-maker* 1.1.0 might be freely downloaded from
http://asterisk.apod.com/wp/ or
http://astro.shu-bg.net/software/TAC-maker/.
Its installation is simple and does not require installation of *Python*: unzip of the archive and run the file TAC-maker.exe.

You can suggest a feature or report a bug on our GitHub page at
https://github.com/acshu.

Acknowledgements

The research was supported partly by funds of project RD-08-244/13.03.2014 of Shumen University.

References

Claret A., 2006, A & A, 428, 1001
Gimenez A., 2006, A & A, 450, 1231
Kipping, D., 2010, MNRAS 407, 301
Kjurkchieva D., Dimitrov D., 2012, IAUS 282, 474
Kjurkchieva D., Dimitrov D., Vladev A., Yotov V., 2013, MNRAS 431, 365
Mandel, K., Agol, E. 2002, ApJ, 580, L171
Seager, S., Mallen-Ornelas, G. 2003, ApJ, 585, 1038
Southworth J., 2008, MNRAS 386, 1644
Southworth J., Maxted P., Smalley B., 2004a, MNRAS 351, 1277
Southworth J., Maxted P., Smalley B., 2004b, ASPC 318, 218