Variable Star and Exoplanet Section of Czech Astronomical Society and Prague Štefánik Observatory

Proceedings of the 41st Conference on Variable Stars Research

Prague Štefánik Observatory, Czech Republic, EU

27th – 29th November 2009,

Chief editor **Radek Kocián**

Participants of the conference in front of the observatory

TABLE OF CONTENT

INTRODUCTION

In November 2009, another national conference on variable stars, stellar astrophysics in general and on extrasolar planets was organised by Variable Star and Exoplanet section of Czech Astronomical Society. The conference was held in beautiful and one of the oldest observatory in Czech republic - Stefanik Observatory in Prague. Our conferences on variable star research provide unique opportunities for meetings between professional and amateur astronomers and have become a crucial platform for exchanging information and sharing knowledge. These events help to keep the local astronomical community alive and active.
This year's conference was held on a weekend from November 27 to November 29. All almost 40 participants were able to witness the richness of our field and the joy that research on variable stars brings to our lifes.
I would like to express gratitude to all authors for their talks and posters and to all participants for their contribution to the discussions!

Luboš Brát
- president of Variable Star and Exoplanet
Section of Czech Astronomical Society

Pec pod Sněžkou, April 15th 2010

NOTES

The scientific content of the proceeding contributions has been refereed by the conference proceedings editors, not by the OEJV editorial board.

A double stellar system HD120136 (tau Boo) with an extrasolar planet: the modelling of insufficient orbital elements

E. PLÁVALOVÁ [1], N.A. SOLOVAYA [2], E.M. PITTICH [2], O.V. KIYAEVA [3]

(1) Dpt. of astronomy, Earth`s physics, and meteorology, Comenius University, Bratislava, Slovakia, plavala@slovanet.sk
(2) Astronomical Institute of the Slovak Academy of Sciences, Bratislava, Slovakia, astrosol@savba.sk
(3) Pulkovo Astronomical Observatory, Russian Academy of Sciences, Pulkovske sh. 65, St. Petersburg 196140, Russia, kiyaeva@list.ru

Abstract: We know more than 420 extrasolar planets only 15 years after the discoveries of the first extrasolar planet. More than 10 percent of planet-hosts are in binary or multiple stellar systems. We don`t know all of the orbital elements for observing extrasolar planets. To calculate the stability of the motion of the extrasolar planet in the binary stellar system, we decided to investigate this by implementing the general three-body problem where we set the three initial conditions. The first - a planet in a binary system revolves around one of the components (parent star). The second - the distance between a star's components is greater than between the parent star and the orbiting planet (ratio of these two distances is a small parameter, less than 0.1). The third - the mass of the planet is much smaller than the mass of the star, but isn't negligible. We can completely solve the three body problem for these initial conditions. In this paper, we will devote some attention to the special case of a near circular orbit of an extrasolar planet. We applied these calculations to the particular specific extrasolar planet HD120136Ab (τ Boo b). For the orbital elements of the distant star we used three different sets which were derived by Hale, Popovic-Pavlovic and Kiyaeva (AMP method). This report has been updated since its presentation at the conference to reflect the new findings.

Abstrakt: Iba 15 rokov po objave prvej extrasolárnej planéty ich poznáme už viacej ako 420. V súčasnosti z celkového počtu objavených extrasolárnych planét sa až 10 percent nachádza v dvojhviezdnych alebo mnohonásobných hviezdnych sústavách. Pre pozorované extrasolárne planéty nepoznáme všetky ich dráhové elementy. Pre výpočet stability dráhy extrasolárnej planéty a modelovania hodnôt chýbajúcich dráhových elementov v dvojhviezdnej sústave môžeme použiť problém troch telies s nasledujúcimi počiatočnými podmienkami. Prvá podmienka – extrasolárna planéta v dvojhviezdnej sústave obieha jeden z hviezdnych komponentov (materskú hviezdu). Druhá podmienka – vzdialenosť medzi hviezdami je omnoho väčšia ako vzdialenosť materskej hviezdy a extrasolárnej planéty (pomer týchto vzdialeností je malý parameter, menší ako 0,1). Tretia podmienka – hmotnosť extrasolárnej planéty je omnoho menšia ako hmotnosť hviezd, ale hmotnosť extrasolárnej planéty sa vo výpočtoch nezanedbáva. Pri týchto troch počiatočných podmienkach sa dá problém troch telies riešiť úplne. V tejto práci sa zaoberáme špeciálnym prípadom a to pohybom extrasolárnej planéty po skoro kruhovej dráhe. Výpočty sme aplikovali na konkrétny príklad – extrasolárnu planétu HD120136Ab (τ Boo b), kde pre dráhové elementy vzdialenej zložky sme použili tri rozdielne s0rie elementov odvodené Haleom, Popovicom-Pavlovicom a Kiayeovou (metódou AMP). Tento článok bol od času prezentácie aktualizovaný a boli do neho zahrnuté nové poznatky.

Introduction

As of January 2010 we know 429 extrasolar planets which are in 363 planetary systems. But only some astronomers realize that more than 10% of all discovered extrasolar planets are members of binary or multiple stellar systems. We know a great number of different type systems with unusual features. One uncommon system is the binary stellar system HD 41004. Astronomers were observing an extrasolar planet orbiting around each of the two stars in this system. Around the component A with a spectral type of K1V and a mass of 0.7 M_{Sun} (mass of the Sun) orbits the extrasolar planet HD41004Ab with a semi-major axis of 1.64 AU and mass of 2.54 M_{Jup} (mass of Jupiter). Around the component B, with the spectral type of M2 and a mass of 0.4 M_{Sun}, orbits the extrasolar planet HD41004Bb with a semi-major axis of 0.0177 AU and a mass of 18.4 M_{Jup}. The next interesting item is a system of multiple extrasolar planets 55 Cnc (HD75732). It is compared with our solar system in many papers, but this system is a wide binary stellar system, its semi-major axis is more than 1050 AU. The A component HD75732A is a star of the spectral type G8V with a mass of 1.03 M_{Sun}, and the B component HD75732B is a star of the spectral type M4 with a mass of 0.026 M_{Sun}. Five extrasolar planets have been observed in this system, with semi-major axes from 0.038 to 5.770 AU and masses from 0.034 to 3.835 M_{Jup}. A register of the binary or multiple systems with hosting extrasolar planets is in the Table 1, created in January 2010.

	Star	Star	Star
GJ676	HD143761 (ρ Crb)	HD200905	HD40979
HD 142 (GJ 9002)	HD143761 (ρ Crb)	HD202206	HD41004
HD 3651	HD16232(30 Ari B)	HD202206	HD47627
HD 3651	HD16760	HD213240	HD75732 (55 Cnc)
HD 45410 (6 Lyn)	HD178911	HD217107	HD75732 (55 Cnc)
HD110014 (26 Vir)	HD186472 (16 Gyg)	HD219449	HD81688
HD114762	HD190360 (GJ 777A)	HD219449	HD8799
HD117176 (70 Vir)	HD192263	HD22049 (ε Eri)	HD89744
HD117176 (70 Vir)	HD192263	HD22049 (ε Eri)	HIP 62157 (HW Vir)
HD121504	HD196885	HD222404 (γ Cephei)	PRS B1620-26
HD125612	HD199665 (18 Del)	HD28254(HIP20606)	SAO72884
HD137759	HD19994	HD33564	V* QS Vir

Table 1: The binary or multiple stellar systems that host extrasolar planets.

The three body problem

For extrasolar planet-hosting stats in binary stellar systems we can use three body problems using the analytical theory (Orlov and Solovaya, 1988) with these three initial conditions: The first condition - a planet in the binary system revolves around one of the components (parent star). The second condition - the distance between the star's components (secondary star) is greater than between the primary star and the orbiting planet (the ratio of these two distances is a small parameter, less than 0.1). The third condition - the mass of the planet is much smaller than the mass of the star, but isn't negligible. The equations of the motions are:

$$\mu_1 \frac{d^2 x_1}{dt^2} = \frac{\partial U}{\partial x_1}, \qquad \mu_2 \frac{d^2 x_2}{dt^2} = \frac{\partial U}{\partial x_2},$$
$$\mu_1 \frac{d^2 y_1}{dt^2} = \frac{\partial U}{\partial y_1}, \qquad \mu_2 \frac{d^2 y_2}{dt^2} = \frac{\partial U}{\partial y_2}, \qquad [1]$$
$$\mu_1 \frac{d^2 z_1}{dt^2} = \frac{\partial U}{\partial z_1}, \qquad \mu_2 \frac{d^2 z_2}{dt^2} = \frac{\partial U}{\partial z_2}.$$

where

$$\mu_1 = \frac{m_0 m_1}{m_0 + m_1}, \qquad \mu_2 = \frac{(m_0+m_1)m_2}{m_0+m_1+m_2}.$$

and index 1 is for the extrasolar planet`s orbit; index 2 is for the distant star`s orbit and U is the potential energy of the system. The motion is analysed in terms of the Jacobian coordinate system and the invariant plane is taken as the reference plane. We used the canonical Delaunay elements L_j, G_j, H_j, l_j, g_j and h_j. They can be expressed in terms of the Keplerian elements as

$$L_i = \beta_i \sqrt{a_i}, \qquad G_i = L_i \sqrt{1-e_i^2}, \qquad H_i = G_i \cos I_i,$$
$$l_i = M_i, \qquad g_i = \omega_i, \qquad h_i = \Omega_i,$$

Where

$$\beta_1 = k \frac{m_0 m_1}{\sqrt{m_0+m_1}}, \qquad \beta_2 = k \frac{(m_0+m_1)m_2}{\sqrt{m_0+m_1+m_2}}, \qquad i = 1,2.$$

In the previous expressions the notations have the standard meanings; m_0, m_2 are the masses of the stars, m_1 is the mass of the planet, k is the Gaussian constant, a_j is the semi-major axis, e_j is the eccentricity, I_j is the inclination of the orbit, M_j is the mean anomaly, Ω_j is the ascending node and ω_j the argument of the perigee. The eccentricity of the star's orbit can have any value from zero to one. We used the Hamiltonian equation of the system without the short-periodic terms. The short-periodic perturbations in the motion of both components, in terms of orbital revolution period, are very small (Solovaya, 1972).

$$F = \frac{\gamma_1}{2L_1^2} + \frac{\gamma_2}{2L_2^2} - \frac{1}{16}\gamma_3 \frac{L_1^4}{L_2^3 G_2^3}\left[(1-3q^2)(5-3\eta^2) - 15(1-q^2)(1-\eta^2)\cos(2g_1)\right]. \qquad [2]$$

Where the coefficients γ_1, γ_2, and γ_3 depend on mass and they can be written as follows:

$$\gamma_1 = \frac{\beta_1^4}{\mu_1}, \qquad \gamma_2 = \frac{\beta_2^4}{\mu_2}, \qquad \gamma_3 = k^2 \mu_1 \mu_2 \frac{\beta_2^6}{\beta_1^4}.$$

and

$$\eta = \sqrt{1 - e_1^2}\,.$$

For the cosine of the angle between the plane of the extrasolar planet's orbit and the plane of the distant star's orbit, the following equation is valid:

$$q = \frac{c^2 - G_1^2 - G_2^2}{2G_1G_2} = \cos(i_1 + i_2)\,,$$

where *c* is the constant of the angular momentum.

The near circular orbit

When we instituted the Hamiltonian [2] into the equations of the motions [1] we got a hyperbolic function in the form of a polynomial of the fifth order. This can be separated into two polynomials of the second and third order, which have the form:

$$f_2(\xi) = \xi^2 - 2(\bar{c}^2 + 3\bar{G}_2^2)\xi + (\bar{c}^2 + \bar{G}_2^2)^2 + \tfrac{2}{3}(10 + A_3)\bar{G}_2^2\,, \quad [3]$$

$$f_3(\xi) = \xi^3 - \left(2\bar{c}^2 + \bar{G}_2^2 + \tfrac{5}{4}\right)\xi^2 +$$

$$+\left[\tfrac{5}{2}(\bar{c}^2 + \bar{G}_2^2) + (\bar{c}^2 - \bar{G}_2^2)^2 - \tfrac{1}{6}\bar{G}_2^2(10 + A_3)\right]\xi - \tfrac{5}{4}(\bar{c}^2 - \bar{G}_2^2)^2\,, \quad [4]$$

where

$$A_3 = 2 - 6{\eta_0}^2 q^2 - 6(1 - \eta_0^2)[2 - 5(1 - q^2)\sin^2 g]\,.$$

For near circular orbits

$$\eta_0 = 1 - \varepsilon\,,$$

where ε is small positive quantity with the condition that the orbit has to be near circular.
For qualitative investigation of motion it is necessary to know the roots of the equations $f_2(\xi)=0$ and $f_3(\xi)=0$. The subscript or superscript 0 denotes initial values of all parameters. The solution of this system of equations has a meaning in the region where $f_2(\xi)f_3(\xi)>0$. All roots are real and positive, but only two of them, ξ_1 and ξ_2, are always less than 1. The meanimg of the variable ξ, which we wish to find, must be defined by the interval $\xi_1 \leq \xi \leq \xi_2$.
So $\xi = 1 - e_1^2$.
We will find the values of the three smallest roots using ony the first order of ε. Then the smallest root of the equatin of the second order [3], which we denote as α_1, is

$$\alpha_1 = 1 + \frac{Q}{4\bar{G}_2(2\bar{G}_2 + q)}\varepsilon\,,$$

and the two smallest roots of the equation of the third order [4], denoted as α_2 and α_3, are:

$$\alpha_2 = 1 + \frac{Q}{4B}\varepsilon\,,$$

$$\alpha_3 = a + \varepsilon\left[(a-1)\left(2a - 5\bar{G}_2 q + \tfrac{5}{2}\right)(1 + \bar{G}_2 q) - \tfrac{1}{4}Q\right]\frac{A + \sqrt{A^2 - B}}{2B\sqrt{A^2 - B}}\,,$$

where

$$A = \tfrac{1}{8} + \tfrac{3}{2}\bar{G}_2^2 + 2\bar{G}_2 q_0\,,$$

$$B = 5\bar{G}_2^2 q_0^2 + \bar{G}_2 q_0 - 3\bar{G}_2^2 , \qquad [4]$$

$$Q = -4\left[2\bar{G}_2^2 + \bar{G}_2 q_0 - 5\bar{G}_2^2 (1 - q_0^2)\sin^2 g_0\right] ,$$

$$a = 1 + A - \sqrt{A^2 - B} .$$

The coefficient Q is always less than zero. The coefficient B may be positive or negative depending on the mutual inclination of the orbits.

1. The mutual inclination of the plane of the extrasolar planet's orbit and the plane of the distant star's orbit is such as $B>0$. Then $\alpha_1<1$, $\alpha_2<1$, $\alpha_3>1$ a $\alpha_1<\alpha_2$. Consequently $\alpha_2\leq\eta^2\leq\alpha_1$. When $\varepsilon \to 0$, $\alpha_1 \to 1$ and $\alpha_2 \to 1$ then $\eta^2 \to 1$. The circular motion is **stable** with respect to e_1 (Cheataev, 1965).
2. When the mutual inclination of the orbits is such that $B<0$, the root α_3 is the smallest root and the lower limit of $\eta^2=\alpha_3$. When $\varepsilon \to 0$, then $\eta^2=a<1$. In this case the circular motion is **unstable**.

Calculation of orbital elements of a distant star by the AMP method

The AMP method (Apparent Motion Parameters) was suggested by Russian astronomer A.A. Kiselev as a method for the determination of the orbit of the Earth' satellites, using only one observation performed by one observe station. This method has been used for calculations of orbits in visual binary stellar systems beginning in 1980. We need long-term observations from one telescope for which the apparent orbital arc covered by observations has been no less than 10°. An orbit was computed through the AMP technique by Kiselev and Kiyaeva (1980). One must know the parameters of apparent relative component motion at the moment T_o: position (ρ,θ), relative velocity μ, its position angle ψ and the radius of curvature ρ_c. We must also know the trigonometric parallax π_t, the relative radial velocity ΔV_r and the masses of the components (M_A+M_B).

$$\Delta V_r = V_r(B) - V_r(A) .$$
$$R = \{\sin\theta\cos\beta , \cos\theta\cos\beta , \pm\sin\beta\} ,$$
$$V = \{\sin\psi\cos\gamma , \cos\psi\cos\gamma , \sin\gamma\} ,$$
$$r^3 = \kappa^2 (\rho\rho_c / \mu^2)|\sin(\psi - \Theta)| ,$$
$$\nu^2 = (\mu/\pi_t)^2 + (\Delta V_r/4{,}74)^2 ,$$
$$\cos\beta = (\rho / \pi_t) / r ,$$
$$\sin\beta = \pm(1 - \cos^2\beta)^{1/2} ,$$
$$\mathrm{tg}\,\gamma = (\Delta V_r / 4{,}74)(\mu / \pi_t).$$

where

$$\kappa^2 = 4\pi^2(M_A + M_B)$$

κ is the dynamic constant of astrocentral motion.

The calculation of the value of a semi-major axis

The third Keplerian law is:

$$a_1^3 = (M_0 + M_2)P_E^2 , \qquad [5]$$

where, P_E is a period of the one orbit of the celestial body in years, M_0 and M_1 are masses of the celestial bodies in terms of mass of the Sun, and a_1 is the semi-major axis of the orbiting celestial body in AU. We can suggest that the third Keplerian law is valid for orbiting stellar bodies, then we could apply this law for the motion of an extrasolar planet around a star (parent star) and the orbital motion of stars in a binary stellar system.
We know the values of the periods of extrasolar planets sufficiently precisely from observations. Moreover, the values of the masses of extrasolar planets and their parent stars may be determined with sufficient precision. Calculating values of the semi-major axis by the third Keplerian equation [5] has been correct. An analogous calculation can be realized for semi-major axis of the distant star. In the calculations we used booth calculating values of the semi-major axis through the third Keplerian law.

The binary stellar system HD 120136

The star HD120136A (spectral type F7V and mass 1.25 M_{Sun}) and the star HD120136B (spectral type M2 and mass 0.37 M_{Sun}) are members of the binary stellar system HD120126 (τ Boo). An extrasolar planet with a mass of 3.9 M_{Jup} is orbiting around the A component of this system. We can find two different sets of orbital elements for the distant star in the catalogue of Doboco et al. (2009). The first sets of the orbital elements of the distant star were calculated by Popovic and Pavlovic (Doboco et al., 2009) and the second set calculated by Hale (1994). The third set of the orbital elements of the distant star was calculated by Kiyaeva in this paper. Here is table of the orbital elements for the extrasolar planet and distant star from different astronomers (Table 2).

	HD120136B (Hale)	HD120136B (Popovic-Pavlovic)	HD120136B (Kiyaeva)	HD120136Ab
Semi-major axis (AU) from external sources	107.9	47.6	$102.75^{+16.65}_{-9.15}$	0.046
Semi-major axes (AU) calculated by third Keplerian law	186.43	62.61	$91.1^{+8.35}_{-7.98}$	0.047
eccentricity	0.91	0.419	0.7±0.12	0.018±0.016
Inclination of the orbit (°)	50.68	72.3	53.5±9.7	-------
Ascending node (°)	28.4	167.8	173.9±11.6	-------
Period days /years	2000y	389.25 y	683.13±91.76 y	3.3135±0.0014 d
argument of perigee (°)	99.34	7.6	339.9±6.1	254

Table 2. The orbital elements for the system HD 120136 from different authors.

The value of the eccentricity of the extrasolar planet is 0.018, which is a suitable value for using the calculations for near circular orbit. We don't know either the inclination of the orbit or the ascending node for the extrasolar planet. We change these unknown values in 1° steps from 0° to 180° for inclinations, and from 0° to 360 ° for the ascending node in each of these six series of calculations. The values of the semi-major axis of the extrasolar planet which we founded into the catalogue, and which was calculated by the third Keplerian law, are nearly the same (Table 2). We used the catalogue's value 0.046 AU in our calculations. We have done six series of calculations, in which the orbital elements for the extrasolar planet remained unchanged. Our further depiction of the slight change in the value of the semi-major axis hasn't changed the results of the calculations. For the orbital elements in the first series of calculations, we used those which Hale (1994) calculated (Figure 1). In the second series of calculations (Figure 2), we used the same orbital elements for the distant star as in the first series of calculations, only changing the value of the semi-major axis, the value of which was calculated by third Keplerian law. The orbital elements for the distant star calculated by Popovic-Pavlovic were used in the third series of calculations (Figure 3). In fourth series calculations (Figure 4), we used the values from the third series, only changing the value of the semi-major axis of the distant star, a value which was calculated by the third Keplerian law. The orbital elements for the distant star derived by the AMP method were used in the fifth series of calculations (Figure 5). In the sixth and last series of calculations (Figure 6), we used all the input values just as in the fifth series of calculations, only changing the value of the semi-major axis of the distant star, the value of which was calculated by the third Keplerian law.

Results of the calculations

A comparison of the results of the first and second series of calculations displayed identical stable regions (Figure 1 and 2). We were able to find the same results, identical stable regions, in comparing these in the third and fourth series of calculations (Figure 3 and 4) and in the fifth and sixth (Figure 5 and 6). We can say that for this system, changes in the value of the semi-major axis, which are not rapid, have no influence on the shape of the orbit or the ascending node of the extrasolar planet. Many observed binary stellar systems with extrasolar planet (-s) are wide systems. When we estimated values of the semi-major axis of the distant star, our degree of error was large. It would be very useful to investigate the maximum range within which changes in the value of the semi-major for a distant star or extrasolar planet do not fundamentally change the shape or range of the stable region for the unknown values of inclination of orbit and ascending node of the extrasolar planet for this system.
To determine more accurately the region of the stability for the unknown values of inclination of orbit and ascending node the extrasolar planet, we put three different series of the calculations (first series, third series and fifth series) in one figure (Figure 7). The stable regions which were calculated for orbital elements of the distant star derived by Popovic-Pavlovic and Kiyaeva have quite large intersections. The stable regions which were calculated for orbital elements of the distant star derived by Hale are in a totally different part of the numerical axes.
Astronomers derived orbital elements have often been unable to identify whether the calculated value is of the ascending or the descending node. We are competent to change the value of the ascending node at 180° for this reason. We computed a seventh series of calculations of the orbital elements derived by Hale, changing the value

of the ascending node at 180°. The stable regions for these series of computations are shown at Figure 8. We put three different calculations of orbital elements, those derided by Popovic-Pavlovic (third series), by Kiyaeva (fifth series), and by Hale with an altered value of the ascending node of the distant star (seventh series) in one figure. We have shown only borderlines for the stable regions for well-arranged in this figure. There are two large intersection regions of the stability on this figure (Figure 9). The first region included values of the inclination of the orbit of the extrasolar planet from 34° to 88° and values of the ascending node of the extrasolar planet form 152° to 209°. The range of the inclination of the extrasolar planet from 92° to 146° and the range of the ascending node of the extrasolar planet from 332° to 29° are the second stable region.

Plans for further study:

We founded two different stable regions of the motion varying unknown orbital elements the inclination of the orbit and ascending node of the extrasolar planet. These two possible stable regions represent possible straight and inverse motion of the extrasolar planet. Using the theory of the three body problems we can determinate the direction of the motion of the extrasolar planet, for which motion stay by the stable.
We showed that a small error in the determination of the value of the semi-major axis of the distant star didn't a significant affect the resulting range of the stable regions of the unknown values of the inclination of the orbit and ascending node of the extrasolar planet for this system. It could be interesting and important to investigate the general maximum range of change in the value of the semi-major axis for the components which didn't fundamentally change of the range of the stable region.

References

Chetaev, N.G.: 1965, Ustojchivost dvizheniya, Fizmatgiz, Moskov.

Docobo, J. A., Ling, J. F., Prieto, C., Costa, J. M., Costado, M. T., & Magdalena P.: 2009, Observatorio Astronómico Ramón María Aller, Catalogue of orbits and ephemerides of visual double stars, http://www.usc.es/astro/catalog.htm.

Hale, A.:1994, Astron.J., 107, 306.

Hartkopf, W.I., Mason, B.D.: 2009, Sixth Catalog of Orbits of Visual Binary Stars, http://ad.usno.navy.mil/wds/orb6.html.

Kiselev, A.A., Kiyaeva, O.V.: 1980, Sov. Astron., 24, 708-716.

SIMBAD Astronomical Database: 2009, http://simbad.u-strasbg.fr/simbad.

Schneider, J.: 2010, Extra-solar Planets Catalogue, *Established in February 1995*, http://exoplanet.eu/index.php.

Solovaya, N.A., & Pittich, E.M.: 2002, Contrib. Astron. Obs. Skalnaté Pleso 32, 117.

Solovaya, N.A., & Pittich, E.M.: 2004, Contrib. Astron. Obs. Skalnaté Pleso 34, 105.

Solovaya, N.A., & Pittich, E.M.: 2006, Contrib. Astron. Obs. Skalnaté Pleso 36, 93.

Solovaya, N.A.:1972, Trudy GAIS, XLIII, vypusk 2, 38.

Orlov, A.A., Solovaya N.A.: 1988, In the Few Body Problem, Ed. M. Valtonen, Kluwer Acad. Publish., Dordrecht, 243.

Figure 1: First series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Hale (1994).
Ω_2=99.34˚, ω_2=28.40˚, i_2=50.68˚, e_2=0.91, a_2=107.90 AU and period is 2000 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

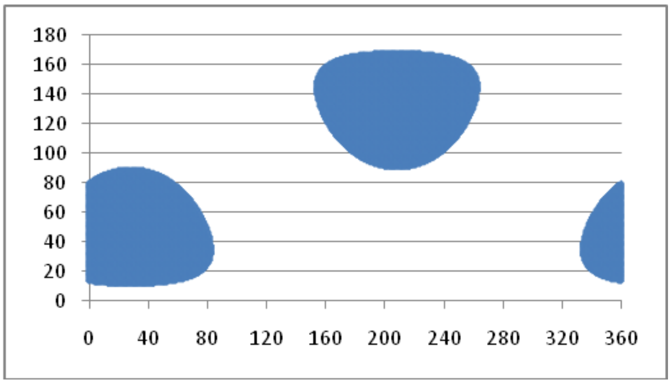


Figure 2: Second series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Hale (1994) and the semi-major axis for distant star was account by third Keplerian law.
Ω_2=99.34˚, ω_2=28.40˚, i_2=50.68˚, e_2=0.91, a_2=186.43 AU and period is 2000 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

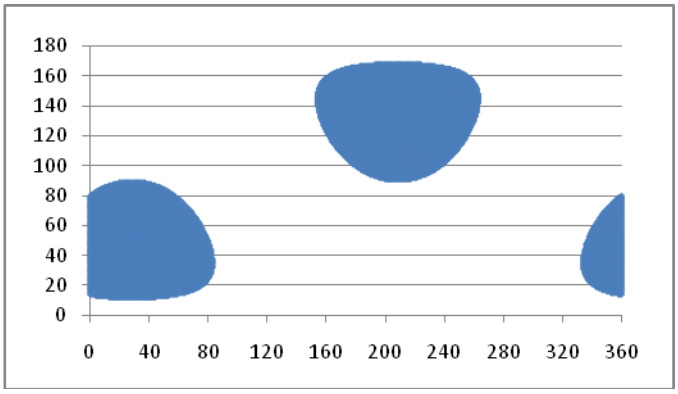


Figure 3: Third series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Popovic-Pavlovic.
Ω_2=167.8˚, ω_2=7.6˚, i_2=72.3˚, e_2=0.419, a_2=47.6 AU and period is 289.25 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

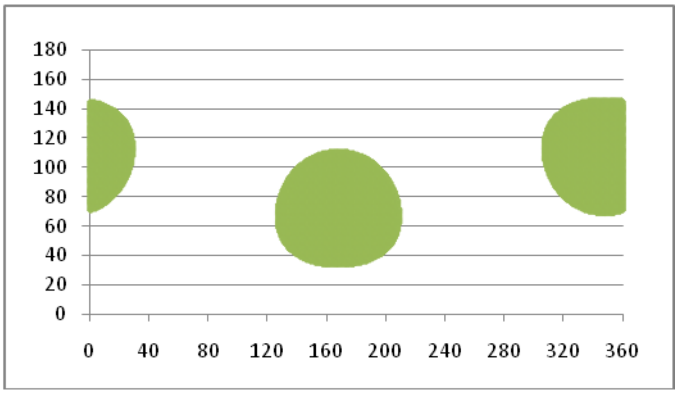


Figure 4: Fourth series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Popovic-Pavlovic and the semi-major axis for distant star was account by third Keplerian law.
Ω_2=167.8˚, ω_2=7.6˚, i_2=72.3˚, e_2=0.419, a_2=62.61 AU and period is 289.25 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

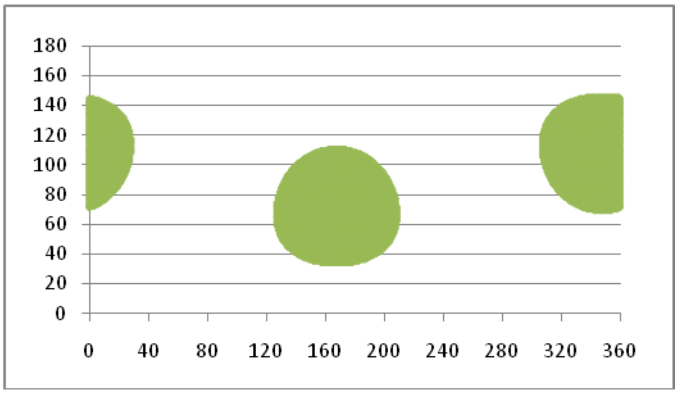


Figure 5: Fifth series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Kiyaeva.
Ω_2=173.9˚, ω_2=339.9˚, i_2=53.5˚, e_2=0.7, a_2=102.75AU and period is 683.13 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

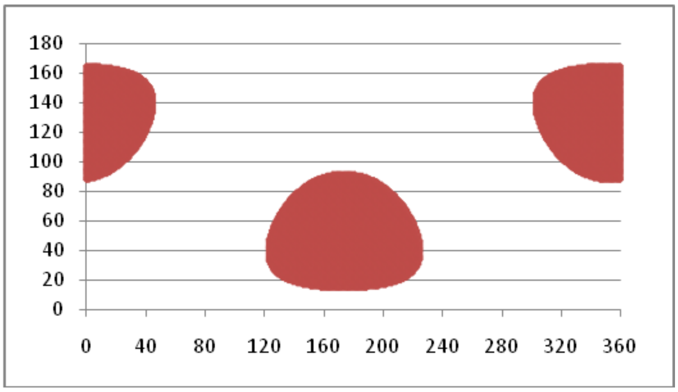


Figure 6: Sixth series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Kiyaeva and the semi-major axis for distant star was account by third Keplerian law.
Ω_2=173.9˚, ω_2=339.9˚, i_2=53.5˚, e_2=0.7, a_2= a_2=91.1 AU and period is 683.13 years.
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

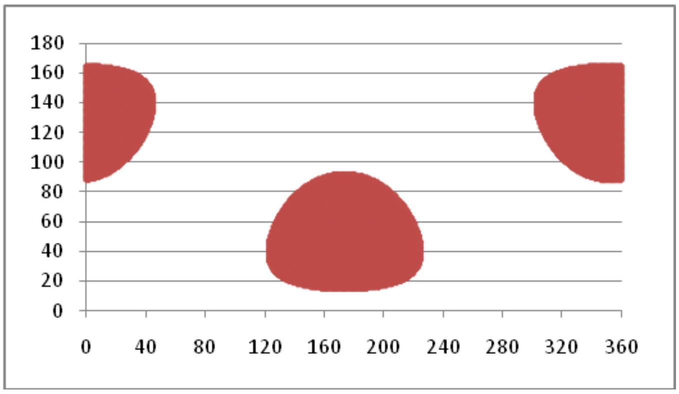


Figure 7: Three different series of the calculations. The borders of the stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Hale (first series), Popovic-Pavlovic (third series) and Kiyaeva (fifth series).

X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

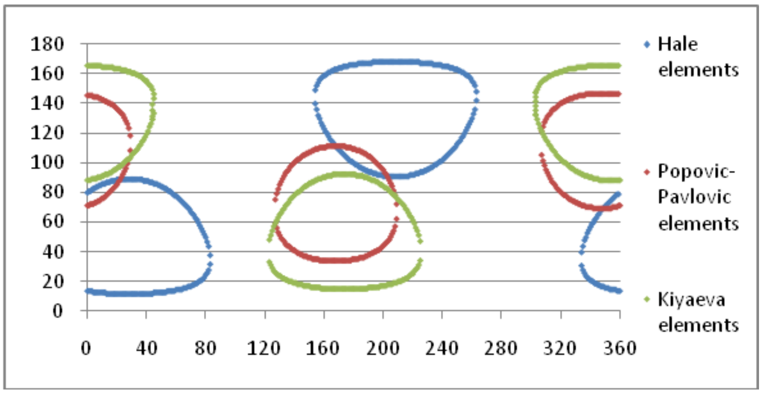


Figure 8: Seventh series of the calculations: The stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Hale with changing value of the ascending node at 180°.

Ω_2=99.34˚, ω_2=208.40˚, i_2=50.68˚, e_2=0.91, a_2=107.90 AU and period is 2000 years.

X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.

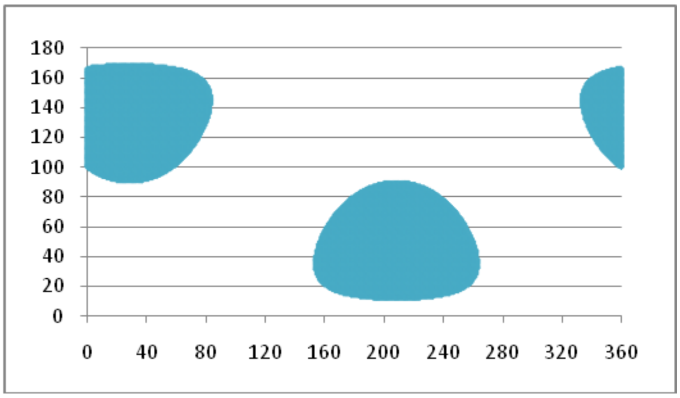
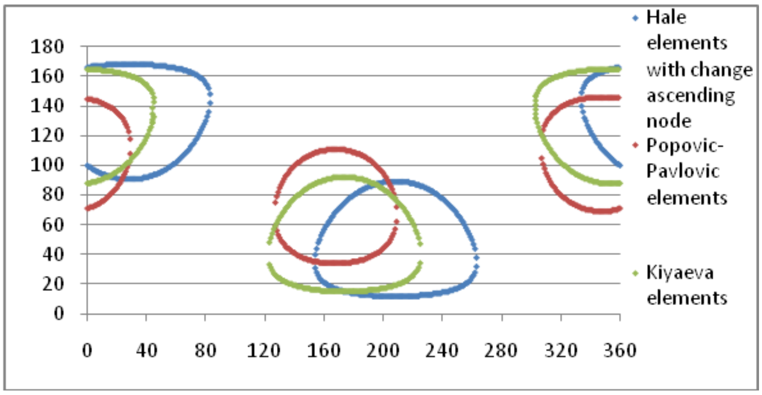


Figure 9: Three different series of the calculations. The borders of the stable regions for the near circular orbit extrasolar planet of the unknown values inclination of the orbit and ascending node the extrasolar planet. The orbital elements the distant star derived by Hale with changing value of the ascending node at 180° (seventh series), Popovic-Pavlovic (third series) and Kiyaeva (fifth series).
X-axis is ascending node for the extrasolar planet (Ω_1) in degree and y-axis is inclination of the orbit extrasolar planet (i_1) in degree.



Eclipsing binaries - interesting cases with changes within O-C diagrams

L. ŠMELCER [1]

(1) Observatory Valašské Meziříčí, Vsetínská 78, 757 01, Czech Republic, lsmelcer@astrovm.cz

Abstract: In 2009 the exploration of the O-C gateway [**1**] was carried out on the server of variable star and exoplanet section of the Czech Astronomical Society). The aim was to look up interesting cases of eclipsing binaries on the base of their O-C diagrams. The described cases indicate that those changes can be caused by the following mechanisms: 1) the presence of the third body 2) there is a system of eclipsing binaries with an eccentric orbit 3) apsidal motion 4) there is a combination of all those effects mentioned above.

Abstrakt: V roce 2009 byla provedena prohlídka O-C brány [**1**] na serveru sekce proměnných hvězd a exoplanet. Cílem bylo vyhledat zajímavé případy zákrytových dvojhvězd na základě průběhu jejich O-C diagramů. Popisované případy naznačují, že tyto změny mohou být způsobeny následujícími mechanismy: 1) přítomnost třetí hvězdy 2) jedná se o systémy zákrytových dvojhvězd s excentrickou drahou 3) stáčení přímky apsid 4) jedná se o kombinaci těchto efektů.

Objects: FZ Del, CU Tau, GP Vul, V 407 Peg

FZ Del

(type EA/SD, period 0,7832115 day, amplitude 10,2 – 11,3 mag).

This is a frequently observed star. The last study was published in 2004 [**2**]. The system can be considered as an early stage of a conservative case of mass transfer. Accurate minima have been measured during last 13 years and we find some indication of O-C diagram periodicity with the amplitude of about 20 minutes. The trend of shortening of the orbital period of binaries was observed by 2008. The observations in September 2009 indicate sudden extending of the period (primary 14th September 2009 – JDhel=2455089.31071, secondary 23th September 2009 – JDhel=2455098.31871, check measure - primary 25th September 2009 – JDhel=2455100.27579). The measure of A. Pasche was looked up in the O-C gateway [**1**] and his minimum in the O-C diagram confirms the change in the trend.

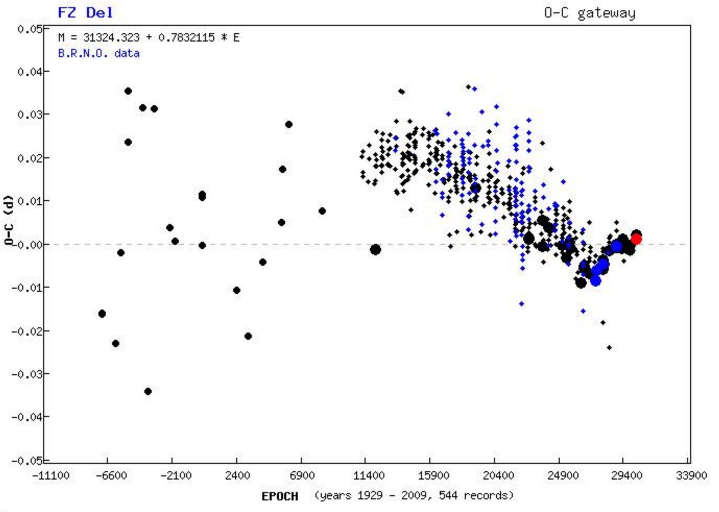


Figure 1: O-C diagram FZ Del. The red point is the last primary minimum observed on 25 September 2009

CU Tau

(type EW/KW, period 0,41253 day, amplitude 11,5 – 11,92 mag)

The last study about eclipsing binaries was published by S. B. Quian **[3].** According to the efemerids published in the work of Yang in 2004 there was a great dispersal in the O-C diagram (up to 0.2 of the day) which indicates an incorrect assesment of the orbital period. This new O-C diagram worked out on the base of the corrected efemerids **[4]** shows very fast shortening of the orbital period. That trend was observed in 2007 (15th October 2007 – JDhel=2454389,43435) and confirmed during the observation in 2009 (31st October 2009 – JDhel=2455136.50549).

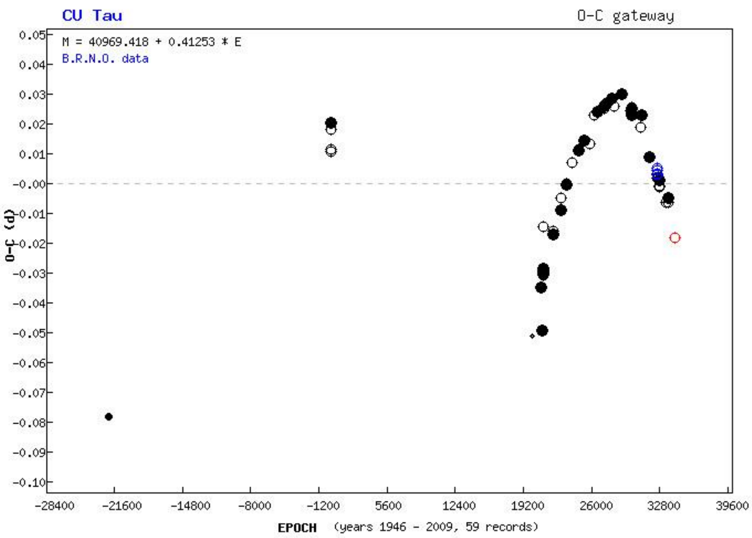


Figure 2: O-C diagram CU Tau. The red circle presents the last secondary minimum observed in 2009.

GP Vul

(type EB/KE, period 1,0325031 day, amplitude 10,7 – 11,9)

A rarely described eclipsing binary. It is mentioned in the work of T. Hegedus in 1988 **[5].** It could be a system with eccentric orbit or with displaced secondary minimum. Older observations in 2005 - 2008 indicate gradual extending of the period, but the observation in 2009 shows a change in this trend. (13th August 2009 – JDhel=2455057,35419, check measure 16th August 2009 – JDhel=2455060,45214)

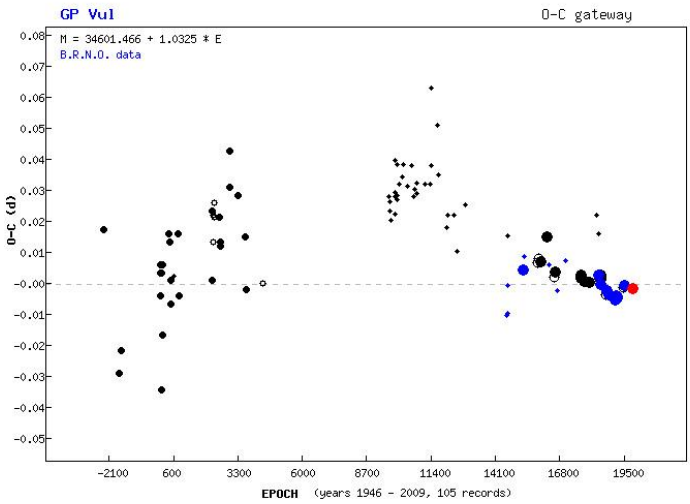


Figure 3: O-C diagram GP Vul. The red point presents the last primary minimum observed on 16 August.2009

V407 Peg

(type EW, period 0,636885 day, amplitude 9,28 – 9,75)

This eclipsing binary was discovered in 2002 **[6]**. Basic parametres of this binary and radial velocity used for the assesment of the star mass ratio were worked out on the base of spectroscopic observations published in 2003 **[7]**. Very few observations are available now but the time difference during primary and secondary minima was apparent as early as in 2002. In the course of the third observing season it seems that primary minimum time starts later and secondary minimum time starts sooner than expected. It might be apsid motion effect. Future observations might confirm this trend.

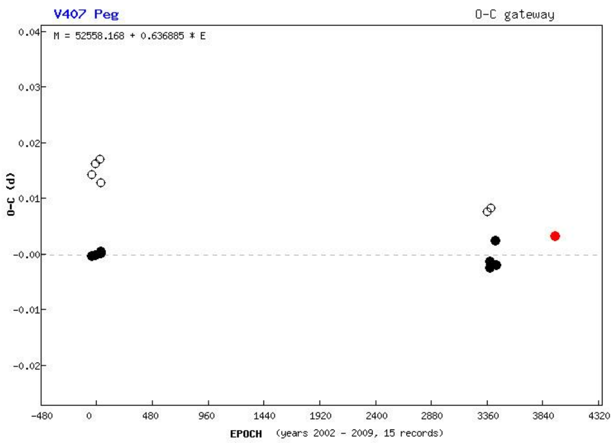


Figure 4: O-C diagram V407 Peg. The red point presents the primary minimum observed in 2009

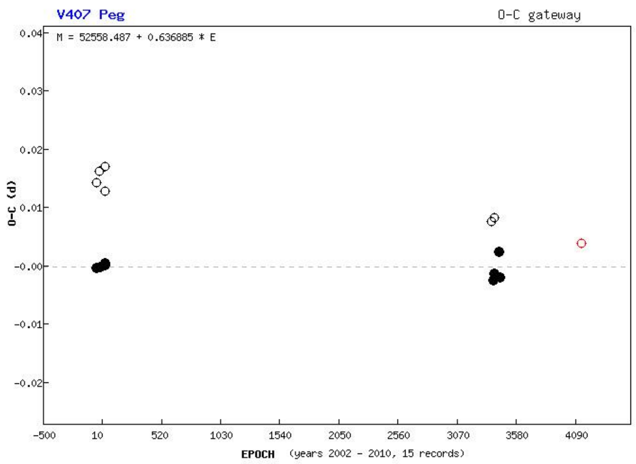


Figure 5: O-C diagram V407 Peg. The red circle presents the secondary minimum observed in 2009

All observations mentioned above were taken at Valašské Meziříčí Observatory on the telescope Schmidt - Cassegrein 0,28-m f/6,3 reflector and SBIG ST-7 CCD camera + V,R and I band filter. CCD frames were mostly reduced by C-MuniPack code **[8]**, the well-known adaptation of MuniPack code (Hroch, 1998), based on DaoPhot routines **[9].** All frames were dark-frame and flat-field corrected first before application of further reduction steps. Minima timings were mostly determined by Kwee-van Woerden method using proram AVE **[10].**

References

[1] http://var.astro.cz/ocgate/

[2] Hanna, M.A., 2004, Study of photoelectric of the eclipsing binary system FZ Delphinus (2004Ap&SS.291…85H)

[3] Qian, S.B., 2005, Deep, low mass ratio overcontact binary systems. III. CU Tauri and TV Muscae (2005AJ….130..224Q)

[4] Yang, Y., 2004, CU Tauri: A W Uma-type system with a small mass ratio (2004Ap&SS.289..137Y)

[5] Hegedus, T., 1988, An updates list of eclipsing binaries showing apsidal motion (1988BICDS..35…15H)

[6] Maciejewski, G., 2002, BD+14 d 5016 – A new EW eclipsing binary (2002IBVS.5343….1M)

[7] Maciejewski, G., 2003, Spectroscopic and photometric solution of the binary system BD+14 d 5016 (2003IBVS.5400….1M)

[8] Motl, D., 2009, C-Munipack, http://c-munipack.sourceforge.net/

[9] Stetson, P.B., 1987, DAOPHOT: A Computer program for crowded-field stellar photometry, PASP **99**, 191 – 222

[10] Barberá, R., 1999, http://www.astrogea.org/soft/ave/introave.htm

On the precision of minimum-time determination

P. ZASCHE [1]

(1) Astronomical Institute, Faculty of Mathematics and Physics, Charles University Prague,
V Holešovičkách 2, Praha 8, CZ - 180 00, Czech Republic, email: zasche@sirrah.troja.mff.cuni.cz

Abstract: A brief discussion about a precision of determination of minima times of eclipsing binaries is presented in this paper. Standard Kwee – van Woerden method was used for symmetric minimum and the numeric result of standard error from the method was compared with the real results and the deviation of minimum times with different settings, apertures and comparison stars. The main result is that the numerical result from the Kwee – van Woerden algorithm is about 10 times lower than the true error of the measurement.

Abstrakt: V tomto článku je prezentována stručná diskuse o přesnosti určení minim zákrytových dvojhvězd. Byla použita standardní Kwee - van Woerdenova metoda určení okamžiku minima pro symetrické minimum a numerický výsledek chyby přímo z této metody byl porovnán s reálnými výsledky a odchylkami okamžiků minim získaných při různém nastavení při redukci, různých velikostech apertur, použitých srovnávacích hvězdách, atd. Hlavním výsledkem zde je, že numerický výsledek chyby z Kwee – van Woerdenovy metody je asi 10x menší nežli reálná chyba daného měření.

Precision of minima times

In many eclipsing binaries their set of times of minima observations is so large that one can use this data for searching for long-term period changes. On the other hand, there are only several eclipsing binaries (EBs), where any period modulation of amplitude below 0.005 day could be detected. Our ability of detecting such a low-amplitude modulation in O-C diagram depends on several effects:

- The coverage of the O-C diagram - the number of data points
- The period of such modulation
- The precision of the individual observations

The last point is discussed here and it depends on the shape of the light curve of the individual binary. In the case of smooth symmetric (and deep enough) minima we are able to observe it very precisely. The mostly used Kwee – van Woerden method [Kwee & van Woerden 1956] is basically build on the assumption of symmetric minimum and good coverage of both descending and ascending branches of the minimum. The parts of the light curve near the minimum itself (or during the total eclipse), as well as the parts outside of the minimum in case of Algol-type binaries, do not have to be covered for a better result of the Kwee – van Woerden method.

Some measurements of minima of different eclipsing binaries provided by astronomers are affected by various observational hitches and their coverage is sometimes quite poor. Some minima cover only small part of descent and the whole ascent, some have very poor coverage of the whole minimum (only a few points), some of them are not symmetric (due to differential photometry and various spectral types of variable and comparison star), etc. All of these effects play significant role in the precision of the resulting time of minimum.

Our analysis

We have used one of our previous observations – namely the secondary minimum of MR Del measured in standard B filter in San Pedro Mártir observatory in Mexico with the 84-cm telescope. Due to the fact that the field of view was rather small (15arcmin), the choice of a proper comparison star was difficult. Using different comparison stars the shape of the minimum was still asymmetric (with bright stars), or the scatter of the individual data points was too large (but the minimum symmetric, with the fainter stars). Therefore, we have tried the following analysis.

The CCD frames have been reduced with the MuniWin programme (http://c-munipack.sourceforge.net/), which is commonly used by the variable-star observers. The reduction process has been done with the different settings. Particularly, the detection threshold (above the background), the size of the aperture (FWHM of the objects), and also the comparison stars have been changing for the different reductions. The result is plotted in Figure 1., where are six different results plotted together. The y-axis denotes the time of minima from the Kwee – van Woerden method for the one setting of the reduction process. The individual error bars show the numerical results from the Kwee – van Woerden method. As one can see, the real scatter of these experimental data points is much larger than the error from the Kwee – van Woerden method, about 10 times. The first one trial was done with the apparently best comparison star, similar brightness and spectral type, but the minimum was not perfectly symmetric. While the later ones have lower brightness, but more symmetric minima. The dotted line in Figure 1. denotes the weighted average of these different minima, which could be used for further analysis.

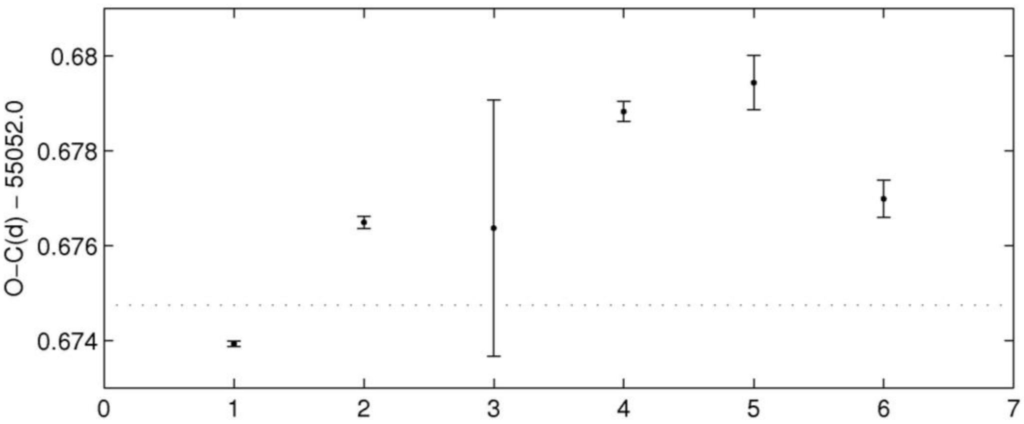


Figure 1: The different reduction processes of one measurement of MR Del.

As one can see from this analysis, searching for period variations in eclipsing binaries with the amplitudes about only 0.001 (about 1.5 min) is still problematic. Especially when one deal with different minima times from different observers and different instruments, different comparison stars and different reduction processes were used. One has to be very careful when using the uncertainties published together with the minima timings.

Conclusions:

The numerical result of the error of time of minimum from the Kwee – van Woerden method has to be used very carefully. This number is only a numerical result and do not tell us anything about the real uncertainty of the measurement. It has to be multiplied 10 times for a better description of the true error of the individual observation. Another important result is that the observer should check the symmetry of the observed minimum with the reduction settings and comparison star used, before submitting the minimum and its error to the journal.

References

[Kwee & van Woerden 1956] Kwee, K.K., van Woerden, H. 1956, BAN, 12, 327

[C-Munipack] http://c-munipack.sourceforge.net/

OPEN EUROPEAN JOURNAL ON VARIABLE STARS
November 2009 http://var.astro.cz/oejv ISSN 1801-5964

Outbursts of binary X-ray sources suitable for monitoring of their optical emission by the amateur observers

V. ŠIMON [1]

(1) Astronomical Institute, Academy of Sciences of the Czech Republic, 251 65 Ondřejov, Czech Republic, simon@asu.cas.cz

Abstract: In this paper we show the possibilities of observing the outbursts in the optical counterparts of binary X-ray sources (dwarf novae and soft X-ray transients). The telescopes for both the visual and CCD observing can be used. These photometric observations are suitable for the scientific analysis of the long-term activity of such systems. We also show that some of these systems display unique and little understood phenomena which are worthy of the optical monitoring. We also emphasize the importance of monitoring of the quiescent levels of both dwarf novae and soft X-ray transients. We show that the brightness of these systems is not constant in this phase of the activity.

Abstrakt: V tomto článku ukazujeme možnosti pozorování vzplanutí optických protějšků binárních rentgenových zdrojů (trpasličích nov a tzv. měkkých rentgenových transientů). Lze použít dalekohledy pro vizuální i CCD pozorování. Tato fotometrická pozorování jsou vhodná pro vědecké analýzy dlouhodobé aktivity uvedených systémů. Rovněž ukazujeme, že v některých z těchto systémů nastávají unikátní a málo prozkoumané jevy, které si zaslouží monitorování. Rovněž klademe důraz na monitorování klidových fází (tedy fází mezi vzplanutími) jak v trpasličích novách, tak v měkkých rentgenových transientech.

Binary X-ray sources

Binary X-ray sources are emitters of radiation over a very broad range of wavelengths, among others in the X-ray and optical bands. Here we focus on the systems whose luminosity is dominated by the light originating from the transferring matter, not from the stellar components. These systems are extremely active in real time. Their wild activity, especially outbursts, makes them very attractive targets for the monitoring. Some of these variations may be cyclic, but they are not periodic. In addition, dramatic changes of the activity on the timescale of years and decades were observed in some systems. The activity on long timescales of months and years remains little studied, although it is very important for our understanding of the relevant physics. A search for and analysis of the dramatic variations like outbursts of various kinds which reflect huge changes of the physical processes are particularly exciting.

These sytems can be divided into cataclysmic variables (CVs) (Warner 1995) and low-mass X-ray binaries (LMXBs) (Lewin et al. 1995). CVs contain a white dwarf which accretes matter from its Roche lobe-filling companion (the so-called donor, usually late type main-sequence star). LMXBs contain a neutron star or black hole which accretes matter in a similar way as CVs do.

The long-term observing in the optical band

Many CVs and LMXBs display large-amplitude variations. Outbursts which occur in some of these systems are particularly prominent events. It is therefore very attractive to make the long-term light curves of such objects. Their variability can be often successfully studied even using visual data. Also CCD detectors become more and more accessible to the amateur observers. They enable them to reach deeper magnitudes and hence to study the states of activity of these systems between the outbursts.

Transitions between the activity states (e.g. outbursts, high/low state transitions) are often fast and unpredictable both in CVs and LMXBs. A part of CVs is often bright enough in the optical band (brighter than ~14 mag). Such systems can be thus observable by the visual observers. Good long-term coverage is thus available at least for some of them. Nevertheless, more deep observations are needed in quiescence between outbursts because most CVs are fainter than 14 mag in this time. LMXBs are often faint in the optical band. They are usually fainter than 16–18 mag except infrequent outbursts, so the existing optical data are often fragmentary or even absent. Nevertheless, the telescopes equipped with CCD detectors can be successful in their observing even by some amateur observers.

Outbursts in dwarf novae

Dwarf novae are a kind of CVs. They display outbursts which are understood in terms of the thermal-viscous instability of the accretion disk (Smak 1984). The typical duration of such an outburst is from several days to one or two weeks. The recurrence time T_C of these outbursts (the cycle length, the interval between the peaks of the neighbouring outbursts) is from several weeks to several months, although exceptions exist (e.g. Warner 1995). A single observation per night may thus be sufficient to cover the profile of the outburst, although a denser coverage is desirable for the often steep rising branch. Investigation of any more general properties of outbursts in dwarf novae deserves the coverage of several outbursts in a given binary. Monitoring is necessary to obtain a sufficient number of the well-mapped outbursts to collect a meaningful ensemble of outbursts.

Usually, dwarf novae are not inactive systems between their outbursts. Some of them display the cyclic variations of the brightness in quiescence, with the typical cycle-length of several years. The typical brightness of many dwarf novae in quiescence is between 14 and 17 mag. This enables us to monitor such systems and to investigate these variations, especially if CCD detectors can be used.

In addition, the state of the long-term activity of at least some CVs is affected by their classical nova explosions. The large influence of these events can be apparent even decades after the explosion. At least some CVs, which were observed to explode as classical novae, display a complicated evolution of their activity after return to quiescence. GK Per (Sabbadin & Bianchini 1983; Hudec 1981; Šimon 2002) and V446 Her (Schreiber et al. 2000) can serve as the examples. Old novae are thus worthy monitoring even after the end the explosion. Establishing any general relation between the type of the post-explosion activity and the properties of the nova explosion is possible only if the dense series of the long-term data for a large ensemble of objects are available.

Outbursts in a special category of CVs, the so-called intermediate polars, deserve special attention. Intermediate polars contain a magnetized white dwarf (e.g. Warner 1995). This magnetic field influences mainly the inner parts of the disk, which is reflected in the profile of the outburst (Angelini & Verbunt 1989). These outbursts are significantly shorter and much less frequent than those in “ordinary” dwarf novae. The activity of DO Dra can be explained by this scenario (Šimon 2000). This system displays rare outbursts with the amplitude of about 5 mag. It reaches the peak magnitude ~10.0–10.5 from the quiescent level of about 15 mag. It is thus easily observable near the peak of the outburst, but one has to bear in mind that the duration of the outburst is about 4 days. Dense observing series is thus desirable. Nevertheless, even monitoring of the quiescent level is attractive because DO Dra is quite active also during quiescence. Its brightness fluctuates on the time scale of days and weeks by more than half a magnitude. The outburst recurrence time of this system is variable and typically it is more than a year. Some intermediate polars display an even more peculiar kind of activity – occasional flares with the amplitude of 1 to 2 magnitudes (e.g. van Amerongen & van Paradijs 1989). The duration of this flare can be even less than a day. The observed recurrence times are uncertain because the data are often fragmentary. It is thus quite possible that many such events in CVs which may be intermediate polars remain unobserved due to insufficient coverage by the data. Clearly, more attention to monitoring of intermediate polars and the investigation of the properties of their long term activity including a search for the outbursts and flares should be paid.

Outbursts in SXTs

Soft X-ray transients (SXTs) are a kind of LMXBs. They display outbursts to some extent similar to those in dwarf novae (Dubus et al. 2001). However, both their duration and recurrence time are generally longer. The typical duration of the outburst is from several weeks to more than a month, while the recurrence time of outbursts is more than a year, although exceptions exist (e.g. Lewin et al. 1995). Since SXTs are often intense X-ray emitters during their outbursts, these events are usually discovered by the X-ray monitors onboard the satellites. Nevertheless, the optical monitoring is important also in this case. A single observation per night may be sufficient to cover the profile of the outburst, although the denser coverage is desirable for the often steep rising branch. The rise of the optical emission to the peak magnitude may even be of the order of a day. In order to obtain a meaningful ensemble of outbursts in SXT, monitoring is necessary to obtain a sufficient number of the well-mapped outbursts in a given system.

In addition, some outbursts of SXTs can possess a complicated profile. A very interesting example is Aql X-1/V1333 Aql. It displayed a peculiar flare during its 1978 outburst (Charles et al. 1980). The nature of this flare is unclear. Since the duration of this flare was considerably shorter than the outburst itself, monitoring in various filters during the outburst is very important. It is quite unclear how common such flares are and whether they are related to the system properties.
Behavior of SXTs in quiescence remains a largely unexplored field mainly because of the faintness of these systems. Most SXTs are fainter than 18 mag in quiescence, so they are beyond the reach of the visual observers.

Nevertheless, even the amateur telescopes equipped with CCD detectors can be able to detect at least some of them. The exposure time of several minutes can suffice to reach down to ~20 mag. Also co-adding the CCD images can be used. Even unfiltered observations are useful here because this approach enables to reach deeper magnitudes. It really seems that surprising and fascinating events can be observed. The quiescence of SXT does not mean a constant brightness. At least some SXTs display the significant variations of their quiescent optical brightness. The long-term optical variations of GS 1354–64/BW Cir observed by Casares et al. (2009) had the amplitude of about 1 mag. The dense series of observations are needed to determine the profile of such variations. It is not clear whether these changes have the shape of small outbursts or gradual waves. Only the monitoring can tell how common or unique such variations are and whether they occur in other SXTs, too.

Conclusions

The dense series of observations are necessary to investigate the properties of the long-term activity of binary X-ray sources. Especially resolving the profiles of the state transitions like outbursts is important for our understanding of the relevant physical processes. It is also important to place these events in the context of the long-term activity of a given system and of a group of systems. Only a long observing series can enable us to form a representative ensemble of events. Of course, the exciting search for the unexpected and unique phenomena can be carried out only by monitoring.

The full details can be found in Šimon (2010).

Acknowledgements:

The support by the grant 205/08/1207 of the Grant Agency of the Czech Republic and the projects D-25-CZ4/08-09 DAAD and PECS 98058 Gaia is acknowledged. This research has made use of the observations from the AFOEV database operated in Strasbourg, France. We thank the variable star observers worldwide whose observations contributed to this analysis.

References

Angelini, L., Verbunt, F., 1989, MNRAS, 238, 697

Casares, J., Orosz, J.A., Zurita, C., et al., 2009, ApJS, 181, 238

Charles, P.A., Thorstensen, J.R., Bowyer, S., et al., 1980, ApJ, 237, 154

Dubus, G., Hameury, J.-M., Lasota, J.-P., 2001, A&A, 373, 251

Hudec, R., 1981, Bull. Astron. Inst. Czechosl., Vol.32, 93

Lewin, W.H.G., van Paradijs, J., van den Heuvel, E.P.J., 1995, X-ray Binaries, Cambridge Univ. Press

Sabbadin, F., Bianchini, A., 1983, A&AS, 54, 393

Schreiber, M.R., Gänsicke, B.T., Cannizzo, J.K., 2000, A&A, 362, 268

Šimon, V., 2000, A&A, 360, 627

Šimon, V., 2002, A&A, 382, 910

Šimon, V., 2010, Advances in Astronomy, accepted, in press

Smak, J., 1984, Acta Astron., 34, 161

van Amerongen, S., van Paradijs, J., 1989, A&A, 219, 195

Warner, B., 1995, Cataclysmic Variable Stars, Cambridge Univ. Press, Cambridge

OPEN EUROPEAN JOURNAL ON VARIABLE STARS
November 2009 http://var.astro.cz/oejv ISSN 1801-5964

The possibilities of CCD photometry of optical afterglows of GRBs

V. ŠIMON [1], C. POLÁŠEK [1], M. JELÍNEK [2], R. HUDEC [1], J. ŠTROBL [1]

(1) Astronomical Institute, Academy of Sciences of the Czech Republic, 251 65 Ondřejov, Czech Republic, simon@asu.cas.cz
(2) Instituto de Astrofísica de Andalucía CSIC, Apartado de Correos, Granada, Spain

Abstract: Gamma-ray bursts (GRBs) are the most luminous events in the Universe. Their gamma-ray emission is often accompanied by the optical emission. Since the duration of this optical emission (the so-called optical afterglow) is much longer than that of the gamma-ray one (hours to more than a day versus at most a few minutes), the optical observations of these events are very promising. In this paper we show the possibilities of observing the optical afterglows with the relatively accessible telescopes equipped with CCD detectors. Such telescopes are able to obtain series of photometric observations, which can be used for the scientific analysis.

Abstrakt: Gama záblesky jsou nejzářivější známé objekty ve vesmíru. Jejich záření v oboru gama je často doprovázeno emisí optického záření. Trvání této optické emise (tzv. optického dosvitu) je mnohem delší než doba, po kterou pozorujeme záření gama (hodiny až více než jeden den oproti nejvýše minutám). Pozorování těchto jevů v optické oblasti je proto velmi slibné. V tomto článku ukazujeme možnosti pozorování optických dosvitů pomocí dostupných dalekohledů vybavených CCD detektory. Takové dalekohledy jsou schopné pořizovat série fotometrických pozorování pro vědecké analýzy.

What gamma-ray bursts are

Gamma-ray bursts (GRBs) are the most luminous events in the Universe. They are uniformly distributed in the sky. These events are not concentrated either toward the Galactic center or toward the Galactic plane (Kouveliotou et al. 1993). Their gamma-ray emission is often accompanied by the optical emission. Since the duration of this optical emission (the so-called optical afterglow) is much longer than that of the gamma-ray one (hours to more than a day versus at most a few minutes), the optical observations of these events are very promising. The relativistic jet radiating via synchrotron process is the dominant source of emission of GRB and its afterglow from the gamma-ray to the optical, infrared, and radio spectral region (Sari et al. 1998).

GRBs can be divided into two groups according to their duration, long (>2 seconds) and short (less than 2 seconds) ones (Kouveliotou et al. 1993). The detection of the optical afterglows of long GRBs (e.g. van Paradijs et al. 1997) showed that they are mostly located in the very distant galaxies. Nowadays, the long GRBs are interpreted as originating from hypernovae, which are very energetic supernovae (e.g. Stanek et al. 2003). This event started when a star collapsed deep inside. A black hole was formed within this star, and within a few seconds a jet of matter was launched. In the later phase of the event, a black hole became embedded by a torus of infalling matter. A jet of a part of this matter outflowing from the star was the dominant source of emission. The origin of short GRBs remains uncertain, although they may occur during a merger in a binary compact system (for example two neutron stars) (Eichler et al. 1989).

Photometric observations using the commonly available filters provide us with important information on the physics of optical afterglows of GRBs. The intensity of the emission depends on the inclination angle of the jet with respect to the observer. The jet has to point almost exactly to the observer to be observable. The brightness of most optical afterglows already falls when they are discovered in the optical band. It is therefore desirable to start observing very soon after the detection of the GRB by the satellite. Typically, power-law decay is observed, but fluctuations may be superimposed on it. The profile of the light curve of optical afterglow is a result of emission from various shocks in the relativistic jet which is propagating through the interstellar medium or the wind of the progenitor (Gomboc et al. 2009).

Deep observations are needed to detect optical afterglow in later phases after the gamma-ray trigger, since most of them are fainter than 18 mag(R) at t-T_0~1 day, although some of them can be brighter than 14 mag(R) in their early phase (at t-T_0 ~ 0.01 day) (Zhang 2007). T_0 is the time of the gamma-ray emission. It is interesting to note here that the brightest optical afterglow ever observed (GRB 080319B) reached peak magnitude 5.8 in its early phase. It was therefore bright enough to be seen with the naked eye (Bloom et al. 2009)! The profile of the light curves suggests that most optical afterglows are the brightest immediately after the gamma-ray trigger, and display a power-law decay later on.

The telescope used for observing the afterglows

We use the robotic telescope called D50. It is located in the Astronomical Institute of the Academy of Sciences of the Czech Republic (AI AS CR) in Ondřejov. It is a Newton system with the parabolic primary mirror 500/1975 mm (Figs.1, 2, 3). To obtain wide field of view of 20 x 20 arcmin, the telescope is equipped with the field corrector TeleVue Paracorr PSB-11000 (Al Nagler). Effective focal length of the telescope with the field corrector is 2277 mm. It contains the focuser DF-2 (Finger Lakes Instrumentation). The instrument is equipped with CCD camera FLI IMG 4710 (CCD chip E2V 47-10, mid-band coating, 1024x024 pixels) and focuser FLI DF-2. The filter wheel FLI CFW-7 contains the *BVRI* filters. Nevertheless, to reach deeper magnitudes, unfiltered observations of the optical afterglow of GRB 090726 shown in this paper were carried out. Their peak sensitivity is close to the *R* filter. Exposure time of 20 seconds was used for each CCD image.

Mode of the telescope control during observing

The telescope is controlled by the software RTS2 developed by Petr Kubánek (Kubánek et al. 2006). This software enables a remote control and operation of the telescope. The software checks the list of objects and observes the selected series of celestial objects using the scripts entered in advance. The example of a successful detection of optical afterglow of GRB 090726 is presented below.

If a GRB is detected by the satellite and the computer, which controls the D50 cm telescope, receives an automatically generated e-mail with its co-ordinates, the software RTS2 evaluates the position of the source in the sky. If the co-ordinates of the GRB enable observing from Ondřejov, any observations of the scheduled objects are interrupted and the telescope begins to observe the field of the GRB to search for its optical afterglow. This strategy has proven to be successful and some optical afterglows were already detected by the D50 cm telescope.

Figure 1: Location of the D50 cm telescope in the white cottage with the sliding roof in the Astronomical Institute AS CR in Ondřejov. The row of the observing cottages is approximately in the north-south direction. The cottage of the D50 cm telescope is situated at the southern end of the row. The sliding roof opens to the North; the upper part of the southern wall can be inclined.

Figure 2: The D50 cm telescope in the observing cottage with the open sliding roof in the Astronomical Institute AS CR in Ondřejov.

Figure 3: The detail of the primary parabolic mirror of the D50 cm telescope in its housing inside the tube. The protecting curtain is not mounted inside the tube in this figure to show the details.

GRB 090726 and its optical afterglow

GRB 090726 was a long GRB localized by the telescope BAT onboard the American satellite *Swift* on 26 July 2009 at 22:42:27.8 UT. It displayed a single-peak profile with the duration of 67 seconds (Page et al. 2009). The GRB coordinates were available via GCN Circular within 65 seconds. The resulting light curve of the initial phase of the optical afterglow of this GRB is displayed in Fig.4. The *R* band observations of Moskvitin et al. (2009) were also included. Notice that the data by Moskvitin et al. (2009) fit our unfiltered observations nicely.

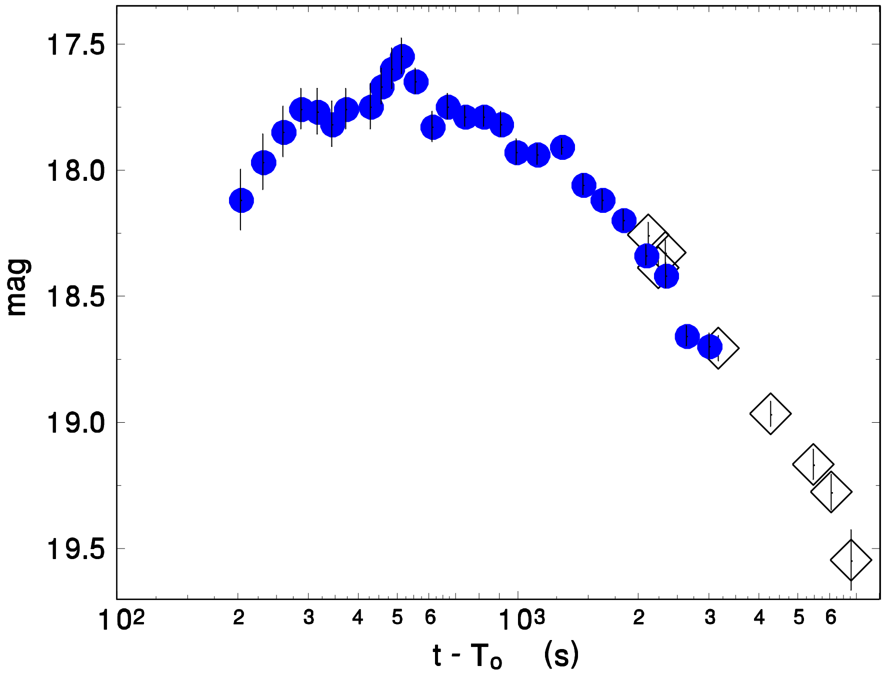


Figure 4: Light curve of the optical afterglow of GRB 090726 in the red spectral region. Closed circles denote the Ondřejov observations. Open diamonds represent the *R* band data of Moskvitin et al. (2009). The error bars (1σ) of each data point are shown. The time elapsed since the GRB trigger is given in seconds.

What the observations enable us to learn about this GRB?

We showed that the light curve of the optical afterglow of GRB 090726 displayed a complicated profile, which can be summarized in the following way. A steep rise of the brightness until t-T_0 ~ 300 s finished with a rapid transition to a plateau lasting until t-T_0 ~ 800 s. A short flare on the flat top (plateau) of the optical light curve at t-T_0 ~ 500 s can be distinguished. The optical emission peaked at ~17.5 mag(*R*) at t-T_0 ~ 500 seconds. Only a slowly steepening decline in 800 s < t-T_0 < 1400 s followed the plateau. Steepening power-law decay at t-T_0 ~ 1400 s lasted until at least until t-T_0 ~ 7000 s. The observations by other observers showed that another break in the decay occurred between t-T_0 ~ 7000 seconds and t-T_0 ~ 0.86 d (see Volnova et al. 2009), that is when our observations must have finished.

Details of the scientific analysis of this afterglow can be found in Šimon et al. (2010). We only briefly summarize its main results. This event was the so-called thin-shell case. It means that the peak of the optical afterglow occurred well after the end of the gamma-ray emission.

We proposed several possibilities to explain the flare in the light curve of the afterglow. Continuing activity of the central engine (that is the central object which produced the GRB) is one possibility. Reverse shock, which is an event occurring in the relativistic jet far from the central object, is also possible. Such a reverse shock can occur in some afterglows far away from the central source and can produce very strong brightenings in the light curve. Our case thus represents only a weak transient brightening in the light curve. In this regard, we note that any additional flash, like the one in GRB 990123 (Akerlof et al. 1999), could occur before the start of Ondřejov observations only if its peak magnitude were comparable to or fainter than that of the peak observed at t-T_0 ~

500 s. The absence of this flash is strengthened by the showing also the first point of Maticic & Skvarc (2009) that the optical afterglow was not brighter than in the subsequent Ondřejov data.

The slow rise of the brightness of the optical afterglow of GRB 090726 speaks in favor of the jet of this GRB propagating through a wind of the progenitor rather than in a homogeneous interstellar medium. The progenitor is the star whose collapse produced the GRB.

The profile of the optical light curve, namely the time of its peak magnitude measured with respect to the gamma-ray emission, enabled us to determine the initial Lorentz factor of GRB. This factor is a measure of the velocity of the jet. GRB 090726 falls into the lower half of the range observed in GRBs and it may even lie at the lower end. Only observations of the early phase of the afterglow which distinguish the time of the peak magnitude enable us to determine this important factor. Let us note that some optical afterglows are relatively bright in this phase. Even small-aperture wide-fileld monitors will be helpful here.

Some optical afterglows were observed to display a re-brightening or a plateau (Klotz et al. 2005) in the phase of the event which corresponds to 3200 s < t-T_0 < 6400 s in the case of GRB 090726. However, GRB 090726 displayed only power-law decay without any plateau.

This optical afterglow belongs to the least luminous ones in the phase of its power-law decay corresponding to that observed for the ensemble of optical afterglows of long GRBs.

Acknowledgements:

The support by the grant 205/08/1207of the Grant Agency of the Czech Republic and the project PECS 98058 Gaia is acknowledged. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester.

References

Akerlof, C., Balsano, R., Barthelmy, S., et al., 1999, Nature, 398, 400

Bloom, J.S., Perley, D.A., Li, W., et al., 2009, ApJ, 691, 723

Eichler, D., Livio, M., Piran, T., Schramm, D.N., 1989, Nature, 340, 126

Gomboc, A., Kobayashi, S., Mundell, C.G., et al., 2009, Gamma-ray burst: Sixth Huntsville Symposium. AIP Conference Proceedings, Volume 1133, pp. 145-150

Klotz, A., Boer, M., Atteia, J.L., et al., 2005, A&A, 439, L35

Kouveliotou, C., Meegan, C.A., Fishman, G.J., et al., 1993, ApJ, 413, L101

Kubánek, P., Jelínek, M., Vítek, S., et al., 2006, SPIE, 6274, 59

Maticic, S., Skvarc J., 2009, GCN Circ.9715

Moskvitin, A., Fatkhullin, T., Valeev, A., 2009, GCN Circ.9709

Page, K.L., Ukwatta, T., Cummings, J., et al., 2009, GCN Report 234.1

Sari, R., Piran, T., Narayan, R., 1998, ApJ, 497, 17

Šimon, V., Polášek, C., Jelínek, M., et al., A&A, 2010, accepted, in press, arXiv:0911.1778

Stanek, K.Z., Matheson, T., Garnavich, P.M., et al., 2003, ApJ, 591, L17

van Paradijs, J., Groot, P.J., Galama, T., et al., 1997, Nature, 386, 686

Volnova, A., Pavlenko, E., Sklyanov, A., et al., 2009, GCN Circ.9741

Zhang, B., 2007, ChJAA, 7, 1

What shall we do with photometric data?

M.CHRASTINA [1,2], M.ZEJDA [1,2], Z.MIKULÁŠEK [1,2]

(1) Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Brno, Czech Republic
(2) The Nicholas Copernicus Observatory and Planetarium, Brno, Czech Republic

Abstract: According to our rough order of magnitude estimate there should be about one million CCD images contained in the Czech archives. However, it is difficult to reach them. Data are stored in several dozens of separated archives, mostly not accessible via internet. Typically, observers put into the public archives only their observing diary and their final results, but no raw data images. We are convinced that now is the time to make a change. We would like to establish common photometric archive containing raw CCD images, that is publicly available. Such an archive would have many advantages such as simpler data search and easier adaptation of the archive to bigger projects such as Virtual Observatory.

Abstrakt: Náš hrubý rádový odhad počtu CCD snímok nachádzajúcich sa na území Českej republiky je jeden milión. Avšak je ťažké sa k nim dostať, pretože sú uložené v niekoľkých archívoch zvyčajne voľne nedostupných. Pozorovatelia zväčša uvoľňujú iba svoje pozorovateľské denníky a výsledky, nie však originálne dáta. Sme presvedčený, že nastal ten pravý čas na zmenu. Pracujeme na založení spoločného voľne dostupného archívu originálnych CCD fotometrických meraní. Takýto archív by mal mnoho výhod, napr. jednoduchšie vyhľadávanie nameraných dát a jednoduchší prenos archívu smerom k väčším projektom ako je Virtual Observatory.

Introduction

Many astronomical measurements are obtained as images. Typical example is the CCD photometry. CCD image is a record of the light intensity measurement of certain part of sky. For many reasons it is almost the only method, which is used in the Czech Republic for observing investigation of astronomical objects. CCD photometry has become very popular and especially very successful. In our country acts many observers and institutions, which are very active in obtaining data. There are scientific institutions such as academy of science and universities as well as public and private observatories.

As we know, photometric CCD observations produce many many computer files. During one night can be obtained thousands of image files and that imply some problems. Such amount of files require large storage space and effective directory structure, if we want the simply orientation in stored data. Also, file format is very important, however about this a little bit later. Some observers solve these problems by deleting data immediately after when data processing is done. This is very bad solution, so we strongly do not recommend this. Please store all your obtained data!

Observers are active for quite a long time, so they can acquire many observing data. According to our rough order of magnitude estimate there should be about one million CCD images contained in the Czech archives. However, it is difficult to reach them. Data are stored in several dozens of separated archives, mostly not accessible via internet, because each observer creates own private archive. Typically, observers put into the public archives only their observing diary and their final results, but no raw data images. Sometimes due to technical problems connected with it, sometimes for other reasons. In extreme case, when observers release nothing, it is difficult even known that the data exist. For these reasons, astronomer looking for certain data must search through many dairies and then pass through hard way to obtain data, which means write emails to observers and ask them for data. However, typical answer is something like this: "I try to look for data, but I do not know where they are... please wait." We can simply say, that astronomers become slaves of dairy searching, data querying and waiting and observers become slaves of data searching. We all definitely agree that this is very bad state for all of us.

There is another issue, which is implied by long-term activity of observers. During that time many things are changed. Technology, instruments, everything is evolving, as well as observers themselves. In result, instruments and other necessary equipment are changing, as well as obsevers' custom practice mostly in storing and archiving data. For this reasons, data are stored in various data format, in non-transparent directory structures and on different storage medium, even through one data archive from one observer. Most of original data archives are very heterogeneous often in unstructured and untidy form not providing an easy survey.

FITS

There is another important thing that must be taken into account. Raw CCD images as a product of CCD photometric measurements are not sufficient themselves. Data processing and further analysis require some additional information, so-called metadata. Metadata are very important descriptive information of the image itself, including binary data format, origin, coordinates, unit systems, instrument parameters, calibrations, ambient conditions, free-form comments and anything else the observer desires. We have to take into the account that data cannot be processed, analysed and interpreted without this necessary additional information. Thus, we need to store all raw data images together with the corresponding metadata.

Unlike the other scientific fields, the astronomy uses the images in FITS format almost exclusively. FITS or Flexible Image Transport System is a digital file format (Wells et al. 1981, Hanisch 2001, e1), in which data and metadata are stored together in one file. Thus, FITS file consists of two parts: header and data block. The image metadata is stored in the header in a human readable ASCII format, which is the major feature of the FITS format.

Now, we would like to give a short introduction into the FITS basics, namely the FITS header and the FITS terminology. The header has exact size of 36 lines, so-called ASCII card images. Each card image is 80 character fixed-length string. Thus simply said, header is 2880 bytes sized block. Each FITS file consists of one or more such headers, which are interleaved between data blocks. The basis grammar of FITS header card image is given by (Wells et al. 1981, Hanisch 2001, e1):

keyword = value / comment

While some keywords are reserved for FITS needs, the FITS Standard allows arbitrary use of the rest of the name-space. Result of this freedom is that too many keywords have the same meaning. For example keywords EXPOSURE, EXPTIME, ITIME they all mean the exposure time of image. Similar problem is that values of keywords have different physical units. For example telescope focal length used to be expressed e.g. in meters or millimeters or even as f-ratio. There exist so-called FITS Standard (Wells et al. 1981, Hanisch 2001, e1), which defines some rules for creating FITS files, but some software rather use own non-standard FITS format.

These facts very complicate automated data processing and also creation of FITS file archives with simple and clear structure. You have to take into account all the possibilities, taking care of ambiguous keywords/units. Therefore, the code will be too long, non-transparent and hard to maintain. Uniform format of FITS headers with set of explicitly defined keywords is the easiest way how to cope with these problems.

General solution

One free accessible archive of raw photometric data, in which images would be stored in one unified format and stored in simply and clearly file structure should be the right solution. Such archive would have some advantages such as simply and quick data search, simpler data processing, possibility of data processing automatization and of course additional possibilities of photometric research, such as investigating of long-term light changes, backward search for events, simpler data compilation from several sources and easier adaptation of the archive to bigger projects such as Virtual Observatory. It is much simpler and efficient to adapt one big and uniform archive than many heterogeneous small archives.

We convince that the best solution is storing raw data images, thus non-calibrated and non-processed. Why? There exist several data processing methods and each of them can be more suitable for something else. In addition, each data processing method contains free parameters, and unfortunately the result of data processing is depend on them sometimes very strongly. Of course, calibration images are necessary, so they must be stored in archive as well, but separately.

All images should be stored in unified format, as close as FITS Standard. Of course, there are some specific requirements, so some modifications and supplementations are necessary. Nevertheless, it is needed to define a set of header keywords with exact meaning. It is clear, that many FITS files do not contain all needful metadata. They will have to be obtained from observers, so intensive communication with observers will be necessary. File structure and astrometric solution must be defined as well. SExtractor (Bertin, E., Arnouts, S. 1996) program is seems to be a good astrometric solution. Everything of this has one clear goal, everybody should obtain all raw images with all necessary calibrations and complete information to data processing in own way.

Our implementation

As we mentioned above, there are many FITS files. Even one observing run can consists of thousands of images. Usually, we have more runs, sometimes from more observers and/or from more observatories. Manual data processing would take years. Thus, we need the computers, what generally means to write the code. Today the most of the tasks will finally turn to computer programming. There exist many programming languages, each of them is suitable for different kind of task. So, we have many possibilities to choose. How should we choose the right one? We do not have enough time to learn of all of them, thus we have to make a good choice at the first place.

There are some properties that the chosen language should have. It should run on various operating systems. Very important is that it should be wide-spread, used by large community. In this case, we can expect that many tutorials, guides, manuals, forums to found on the web. It should be multi-purpose, usable for many kind of tasks. Also, standard libraries are very important, because they offer solutions for many tasks.

We made such a choice. Python (e2) is a multi-platform high-level object-oriented programming language, which covers most of properties mentioned above. It has very intuitive syntax, so everybody can really learn it in a few days. The development in Python is less time-consuming that in low-level languages, such as C. That all makes Python very powerful and effective tool for coding. Python is distributed under an OSI-approved open source license that makes it free to use, even for commercial products.

The PyFITS library (Barrett, P. E., Bridgman, W. T. 1999, Barrett, P. E., Bridgman, W. T. 2000, e3) provides an interface to FITS formatted files under the Python. For manipulating FITS files, we choose this library. It is a development project of the Science Software Branch ate the Space Telescope Science Institute, the current stable version is v2.2.2 (2009, October 12). Project is clearly live, that is very important.

MUNI-FITS-Utils

MUNI-FITS-Utils is a package of Python scripts, which have been developed in PyFITS library. Scripts are user-friendly and allow manipulating FITS headers and FITS files. At current state the scripts perform two tasks. First, they convert FITS headers into the required format. Second, they rename FITS files following specified naming convention and sort them into standard directory structure. This is very useful for simple maintenance of CCD image archive.

First tasks is managed by two scripts. First script can handle single modification of keyword, value and comment. The required action, such as adding, changing, removing, renaming etc. is specified by documented command line argument(s). Second script is a batch file, which uses the first script to modify whole FITS header into the standard format, according to our rules. Functionality will be extended in very near future. Although scripts have been developed under OS Linux, they can be easily adapted to other operating systems.

During coding comes some problems. Most of them implies with the fact, that there is no reference manual of the PyFITS library available. The “PyFITS User's Manual” (e3) is just a simple tutorial, with lacks a lot of important details. Some problems had to be solved using the trial-and-error method. Also some of the PyFITS functions slightly decline from the desired functionality. However, it is hard to face it due to unavailability of the reference manual.

Conclusion

For the reasons mentioned above, we would like to establish common photometric archive containing raw CCD images, that is publicly available. At this moment we work very intensively on the final technical design and implementation. We have already defined a set of standard keywords, we established rules for their usage, following the original FITS Standard as much as possible. Standard name convention for the directory structure and file-names is almost complete. Development version of the necessary codes providing necessary support for automated import of any data archive into this project is already available. Also we have roughly about 250 000 images collected from various data archives and we continue in acquisition of more data. We would like to encourage you to participate this project in order to establish next generation archive for future astronomy.

Acknowledgements:

This work has been supported by grant GAAV IAA301630901. The SAO/NASA Astrophysics Data System was used in preparation for this paper. Thanks to Gabriel Szász for language corrections.

References

Barrett, P. E.; Bridgman, W. T. 1999, ASPC, 172, 483B

Barrett, P. E.; Bridgman, W. T. 2000, ASPC, 216, 67B

Bertin, E.; Arnouts, S. 1996, A&AS, 117, 393B

Hanisch, R. J., Farris, A., Greisen, E. W., Pence, W. D., Schlesinger, B. M., Teuben, P. J., Thompson, R. W., Warnock, A., III 2001, A&A, 376, 359

Wells, D. C., Greisen, E. W., Harten, R. H. 1981, A&AS, 44, 363

The FITS Support Office at NASA/GSFC, http://fits.gsfc.nasa.gov, [e1]

Python Programming Language, http://www.python.org, [e2]

PyFITS, 2009, http://www.stsci.edu/resources/software_hardware/pyfits, [e3]