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SEMINAR - 4. LETNIK

Eclipsing binary stars

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Abstract

Observations indicate that the majority of stars have a companion, thus that stars are in more than 50 % of all cases united in a system of two or more stars. In this seminar we will introduce binary stars, especially eclipsing binary stars that are one of the most important binaries, because of their geometrical layout. Further on, we will present methods of data acquisition, basic geometry and physics for understanding binaries.

Contents

1 Introduction

In the dark night sky we see a lot of stars and it looks like some stars are very close together. Proximity of two stars is apparent in some cases due to the effect of projection of stars according to an observer. But we also see stars that are gravitationally bound and their proximity on the night sky is not just the effect of projection. When both stars are visible, sequence of observations would indicate that the stars move around a common center of gravity.

Observations indicate that majority of stars have a companion, thus that stars are in more than 50 % of cases united in a system of two or more stars [1]. Multiple systems consist of stars which are gravitationally bound and move around a common center of gravity. Systems of multiplicity three and higher are frequent and are representing approximate 20% of the total stellar population, but higher is the number of stars in system, lower is the number of known systems [2]. Double stars, or in a shorter term binaries, are important because they are numerous and we can compare them among themselves. They are also the main source of our knowledge on basic characteristics of stars, because we get their values of masses, temperatures, luminosities, radii. . . with modeling. There are more types of binary stars, that are classified in accordance to their observational characteristics [3]:

- Optical double stars: They are not gravitational bound, but we see both components with a telescopic eyepiece or with a naked eye. So they just simply lie along the same line of sight and they are not true binaries. We can not determine any physical parameters apart from those obtainable for single stars.

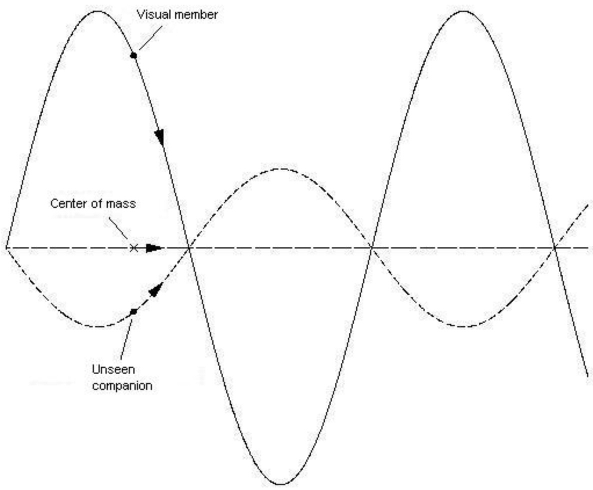

Figure 1: An astrometric binary, which contains one visible member. The unseen star is implied by the oscillatory motion of the observable star [4].

- Astrometric binaries: If only one component is visible and the other one is too faint or is too close to its brighter companion, we cannot observe both components of the double system with telescope. That this bright star has a companion we detect by astrometric methods. Astrometry measures and explains the positions and movements of stars and other celestial bodies. If only one star is present, it moves on a straight line. But in binary or multiple system orbital motion is different. In this case the unseen component is implied by the oscillatory motion of the observed element of system as shown in figure 1 [4].
- Spectroscopic binaries: In this case the components are so close to one another that even with a high resolution telescope, we are unable to observe both members directly. We can detect the presence of the binary system via Doppler effect.
- Eclipsing binaries: If the line of sight of the observer lies close to the orbital plane of the system we can witness eclipses: the part of the light is blocked as one component passes in front of the other, the observed flux is diminished. Such a time-dependent change in flux enables us to further constrain the physical parameters of binary system. Eclipses can be used to obtain: inclination, stellar masses and radii, orbital eccentricity, effective temperatures... Eclipsing binary system could also be spectroscopic or astrometric system at the same time if we can see eclipses.

Binary stars are also ideal distance estimators, since absolute magnitudes of the components may be readily obtained from luminosities, as it is shown in chapter 3.3. This way the distances to the Magellanic Clouds, galaxies M31 and M33 had been determined [5].

2 Methods of data acquisition

Before modeling and studying eclipsing binaries we must have some measurements. In this chapter we will present methods to obtain diverse and accurate observational data. Eclipsing binary studies involve combination of photometric and spectroscopic data.

2.1 Photometry

This is the most popular and accessible method in astronomy. Photometry is the measurement of the intensity of electromagnetic radiation usually expressed in apparent magnitude. Apparent magnitude is a numerical scale to describe how bright each star appears in the sky. The lower the magnitude, the brighter the star. Because the stars are on different distances from Earth and brightness depends on this distance, we introduce absolute magnitude. This is defined as the apparent magnitude a star would have if it was located at a distance of 10 parsecs from us ($1pc \approx 3.26$ light-years) [4].

The photometry measurement is done with an instrument with a limited and carefully calibrated spectral response. Photoelectric detectors convert light into an electrical signal. There are three detector types: the photomultiplier tube, photodiode and charge-coupled device (CCD) [6]. The CCD devices are most commonly used nowadays. These are solid-state devices with an array of picture elements called pixels. Each pixel is a tiny detector – a CCD array can have thousands to one million or more pixels. CCDs are very sensitive to light over a wide range of wavelengths from the ultraviolet to infrared, and can measure many stars at once in contrast to photomultiplier tubes and photodiodes that measure one star at a time [6]. Even the amateur astronomers can easily use it.

Photometric measurement consists of acquiring a flux on a given pass-band in a given exposure time. A pass-band is the range of wavelengths that can pass through a filter without being attenuated. That gives us photometric light curve, which reveals variability of the source. If variability is periodic, it is customary to fold the observational data to phase interval [0,1] or [-0.5, 0.5]: $\Phi = (T - T_0)/P$, where T is heliocentric Julian date (astronomers use Julian calendar), T_0 is reference epoch and P is period. With this transformation we construct a phase light curve. Then from phased light curve, we can extract physics parameters, like temperature ratio, radii of both components...

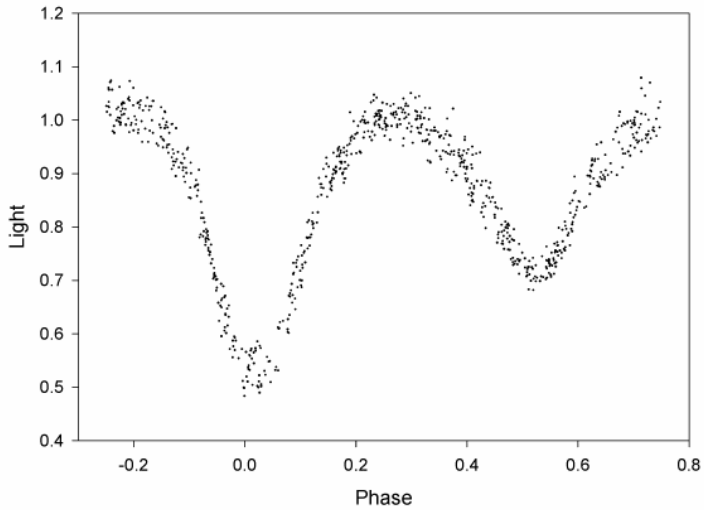

Figure 2: Photometric light curve of Beta Lyrae, an eclipsing binary system. It presents the change of magnitude as a function of orbital phase [7].

Figure 2 presents a phase light curve where the phase is defined to be 0.0 at the primary minimum. Primary minimum is deeper and occurs when the hotter star passes behind the cooler one, because luminosity of the star is define as $L = 4\pi R^2\sigma T^4$. On the other hand, secondary minimum occurs when the cooler star passes behind the hotter one.

2.2 Spectroscopy

Spectroscopic measurements are based on dispersing the beam of light into the wavelength-distributed spectrum. Resolution of the spectrum is defined as [3]:

$$R = \lambda/\Delta\lambda \tag{1}$$

where $\Delta\lambda$ is the smallest wavelength resolution element of the instrument which is being used. Details of the spectrum are important, so we need a really high resolution. $R \sim 5000$ corresponds to medium resolution, where strong spectral lines can be studied, if $R \sim 20000$ (high resolution) we can study narrow spectral lines [1]. From measuring the changes of spectral line positions in time, we can obtain radial velocity of the source. And by measuring the changes in spectral line shapes in time, we can do Doppler tomography of the source [1]. Doppler effect for distant objects (for example galaxies) is very large, but for closer objects like binary stars the Doppler effect is very small, so a high level of resolution is important. Once we have radial velocities, a radial velocity curve may be assembled by listing radial velocities as function of time or phase. Figure 3 shows velocity curve as a function of time, according to position of the stars. When the star moves away from us, the velocity is defined as positive and when stars move in our direction the velocity is negative. In some way this curve is similar to a light curve, but we get different physical parameters, like mass ratio, eccentricity, semi-major axis...

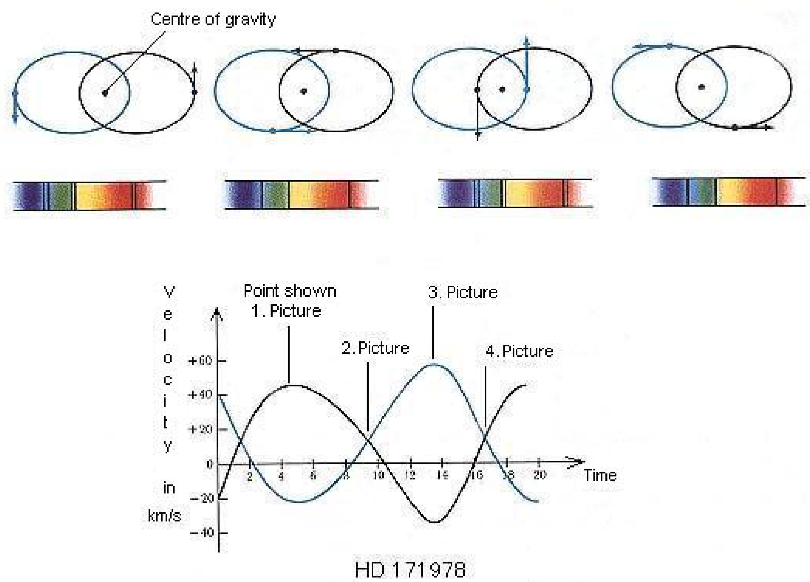

Figure 3: Observed radial velocity curve as a function of time. Picture shows how curves are changing according to the star's position. The observer and the orbital plane are both in the plane of the paper [8].

3 System geometry

In this chapter we will briefly familiarize ourselves with the basic physics for understanding eclipsing binaries.

3.1 Roche lobe

In a binary system stars can be more or less apart. If the stars are close, they will influence each other and they will change their shape. Star's external envelope will strongly increase and deform from circular to a teardrop-shape. The Roche lobe is the region of space around a star within which orbiting material is gravitationally bound to that star. Binary systems are classified into tree classes: detached, semidetached and contact systems, as is shown in figure 4 [4].

Binary stars with radii much smaller then their seperation are nearly spherical and they evolve nearly independetly [4]. This system is a detached system. These binaries are ideal physical laboratories for studying the properties of individual stars. If one star expandes enough to fill Roche lobe, then the transfer of mass from this star to her companion can begin [4]. Such system is called a semi-detached binary system. In case when both stars fill, or even expand beyond, their Roche lobes stars share a common atmosphere [4]. Such a system is called a contact binary sytem. In this seminar I will only present detached binary systems.

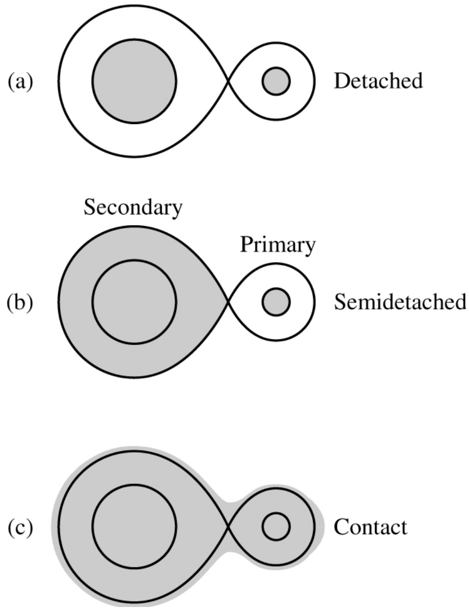

Figure 4: Figure shows classes for binary stars system. They are classified into three clases: detached, semidetached and constact systems [4].

3.2 Kepler's law

Motion of stars in a binary system around the mutual center of mass constitutes a classical two-body problem. Kepler third law gives us an equation:

$$\frac{a^3}{t_0^2} = \frac{G(m_1 + m_2)}{4\pi^2} \tag{2}$$

where m_1 and m_2 are point masses of individual stars, t_0 is orbital period and a is separation between them. This formula also applies for binary stars, because of the universality of the gravitational force [4]. From this formula we can also express the angular frequency of the orbit ω:

$$\omega^2 = \left(\frac{2\pi}{t_0}\right)^2 = \frac{G(m_1 + m_2)}{a^3} \tag{3}$$

When binary stars are very close then this angular frequency of the orbit is equal to the stars rotation.

3.3 Magnitude, distance and luminosity

In chapter 2.1 we talked about magnitudes. The brightness of a star is measured in terms of the radiant flux j received from the star. Radiant flux is a total amount of light energy of all wavelengths that falls on oriented perpendicular area per unit time [4]. Radiant flux received from the star depends on intrinsic luminosity and the distance from the observer. The equation for star flux j with luminosity L is: $j = L/(4\pi r^2)$. If we observe two stars with apparent magnitude m_1 and m_2 in relation to their flux ratio, the equation is [4]:

$$m_1 - m_2 = -2.5 \log_{10} \left(\frac{j_1}{j_2} \right) \tag{4}$$

We already explained the difference between absolute and apparent magnitude in chapter 2.1, but we did not write down the connection, which is called the star distance modulus [4]:

$$m - M = 5 \log_{10} \left(\frac{d}{10pc} \right) \tag{5}$$

where m is apparent and M absolute magnitude, d is the distance to the star and $10pc$ is a distance of 10 parsecs. We are able to measure apparent magnitude and if we could somehow measure or calculate the absolute magnitude, we would have no problem calculating the distance to the star.

Using the equation (4) and considering two stars at the same distance, we see that the ratio of their flux is equal to the ratio of their luminosities. So we could rewrite equation (5): $100^{(M_1 - M_2)/5} = L_2/L_1$, where M_1 and M_2 are absolute magnitude of both stars. Our nearest star is the Sun and we have a lot information about it. By letting one of these stars be the Sun, then we get the relation between a star's absolute magnitude and its luminosity:

$$M = M_\odot - 2.5 \log_{10} \left(\frac{L}{L_\odot} \right) \tag{6}$$

3.4 Eccentricity

In chapter Spectroscopy we see that we can measure radial velocity, which depends upon the position of the stars. The shape and amplitude of the curve depends upon the eccentricity of the orbit and on the angle from which we observe the binary (inclination). If the plane of the star system lies in the line of sight of the observer ($i = 90°$) and the orbit is circular, then the radial velocity curve will be sinusoidal [4]. But if the inclination is not $i = 90°$, then only amplitudes on the curve change by the factor $\sin i$. In some cases the orbit is not circular and radial velocity curve changes the shape and becomes skewed, as shown in figure 5 [4]. Motion of a star is affected by the attraction from the other star. The star moves faster when it is nearer to the companion and slower when it is further, so velocity curve become skewed.

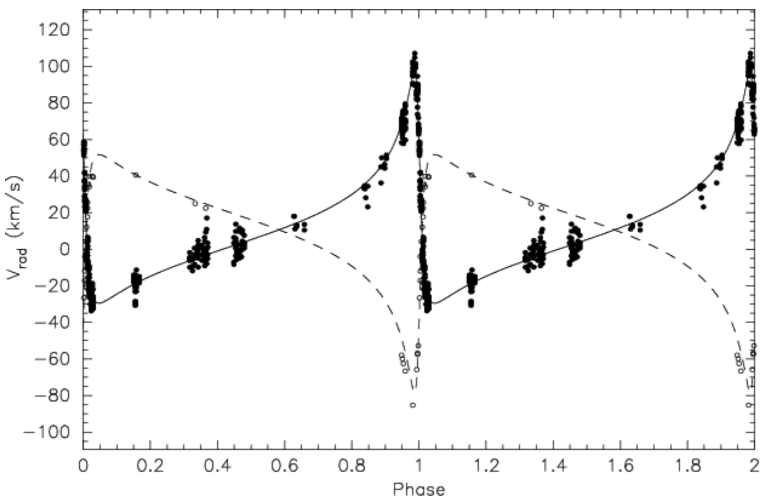

Figure 5: Radial velocity curve for two stars in elliptical orbits. The curve is not sinusoidal, like in the case of a circular orbit, but it becomes skewed [9].

3.5 Mass and velocity

Interacting two-body system or many-body system is most easily solved in the reference frame of the center of mass. If we assume that all of the forces acting on individual particles in the system are due to other particle contained within the system, Newton's third law requires that the total force must be zero:

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = M\frac{d^2\mathbf{R}}{dt^2} = 0 \tag{7}$$

where M is total mass of the system.

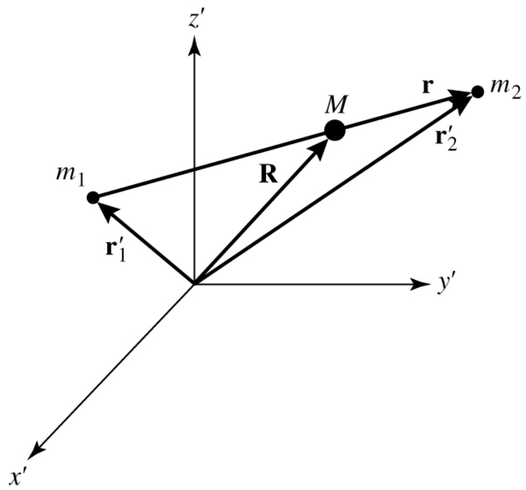

Figure 6: Coordinate system indicating the position of m_1, m_2 and the center of mass (located in M) [4].

Equation for center of gravity is:

$$\mathbf{R} = \frac{m_1\mathbf{r_1'} + m_2\mathbf{r_2'}}{m_1 + m_2} \tag{8}$$

but if we choose a coordinate system for which the center of mass coincides with the origin of coordinates then the upper equation must be zero. In figure 6 we see a connection: $\mathbf{r_2'} = \mathbf{r_1'} + \mathbf{r}$ and from equation (7) it follows:

$$\mathbf{r_1'} = -\frac{m_2}{m_1 + m_2}\mathbf{r}$$
$$\mathbf{r_2'} = \frac{m_1}{m_1 + m_2}\mathbf{r} \tag{9}$$

If we consider only the lengths of the vector $\mathbf{r_1'}$ and $\mathbf{r_2'}$ we find out:

$$\frac{m_1}{m_2} = \frac{r_2'}{r_1'} = \frac{a_2}{a_1} \tag{10}$$

where a_1 and a_2 are the semi-major axes of the ellipses. If we assume that the orbital eccentricity is very small, then the velocity of stars are $v_1 = 2\pi a_1/t_0$ and $v_2 = 2\pi a_2/t_0$. From chapter 3.4 we know that the velocity depends on inclination and radial velocity for both stars are $v_{1r} = v_1 \sin i$ and $v_{2r} = v_2 \sin i$. If we carry this in equation (10) we get:

$$\frac{m_1}{m_2} = \frac{v_{2r}}{v_{1r}} \tag{11}$$

3.6 Inclination, radii and temperature

Inclination i is the angle between the orbital plane and plane-of-sky [1]. It can assume any value on the interval $[0, 90°]$, where $i = 0°$ means that we look on the plane of the system face on and if $i = 90°$, then we see a binary from the edge.

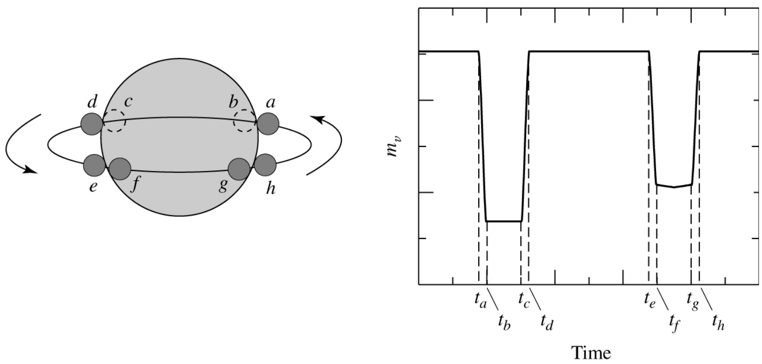

Figure 7: The light curve of eclipsing binary for which is $i = 90°$. From the times indicated on the light curve we can get radii for both stars [4].

From a phase light curve, more exactly from duration of eclipses, we can get the radii of each member. Referring to the figure 7, the amount of time between first contact (t_a) and minimum light (t_b), combined with the velocities of the stars, lead directly to equation of the radius of smaller star and similarly for a bigger star for second eclipse [4]:

$$r_s = \frac{v}{2}(t_b - t_a)$$
$$r_l = \frac{v}{2}(t_c - t_a) = r_s + \frac{v}{2}(t_c - t_b) \tag{12}$$

where r_s is radius of small star, r_l is radius of large star and $v = v_s + v_l$ is the relative velocity of two stars.

From the light curve we can also obtain the ratio of effective temperatures of the binaries. This is obtained from the dip of the light curve and the deeper the dip is, the hotter star passing behind its companion is. Stefan-Boltzmann equation connects total energy radiative surface flux with temperature: $j = \sigma T^4$. This law applies only for perfect black bodies, an assumption which does not apply to real stars, thus we use this equation to define the effective temperature T_e of star's surface [4]:

$$j_{surf} = \sigma T_e^4 \tag{13}$$

Assuming that the observed flux is constant across the disk (but we know that is not true, in here we will neglect this), then the amount of light when we do not see eclipses is given by:

$$B_0 = k(\pi r_l^2 j_{rl} + \pi r_s^2 j_{rs}) \tag{14}$$

where k is a constant that depends on the distance of the system and the nature of the detector [4]. Light detected during the primary minimum (B_p) and secondary minimum (B_s) is [4]:

$$B_p = k\pi r_l^2 j_{rl}$$
$$B_s = k(\pi r_l^2 - \pi r_s^2) j_{rl} + k\pi r_s^2 j_{rs} \tag{15}$$

Because we can't determine k exactly, we must see ratios. From the ratio of the depth of primary to the depth of the secondary minimum, we find out:

$$\frac{B_0 - B_p}{B_0 - B_s} = \left(\frac{T_s}{T_l}\right)^4 \tag{16}$$

4 PHOEBE

There are some programmes and methods for modeling eclipsing binaries but in this seminar we will only mention programme PHOEBE, which stands for PHysics Of Eclipsing BinariEs. It is a tool for the modeling of eclipsing binary stars based on real photometric and spectroscopic data. It is also publicly accessible and was developed by Andrej Prsa (core and scripter development), Gal Matijevič (GUI development), Olivera Latkovič (GUI development, documentation), Francesc Vilardell (Mac ports) and Patrick Wils (core and GUI development). We can get programme on the following website:

`http://phoebe.fmf.uni-lj.si/`

Programme is divided into several tabs – screen pages with selected content that fit into a specific category. At first we must supply information on experimental data. The other tabs hold all parameters that characterize the binary system as a whole, curve-independent parameters that are characteristic to each star individually, parameters that describe the orbit, curve-dependent parameters and parameters that contribute in perturbative orders of corrections to curves (that we did not mention in this seminar) [10]. Finally, the "Fitting tab" contains functions and parameters that define and support minimization algorithms. From changing parameters we adapt synthetically curve to the observed one. When the curves coincide we get the solution for binary system and we also determine all physical parameters. And in the last tab "Star shape" the programme shows us, how the binary system looks.

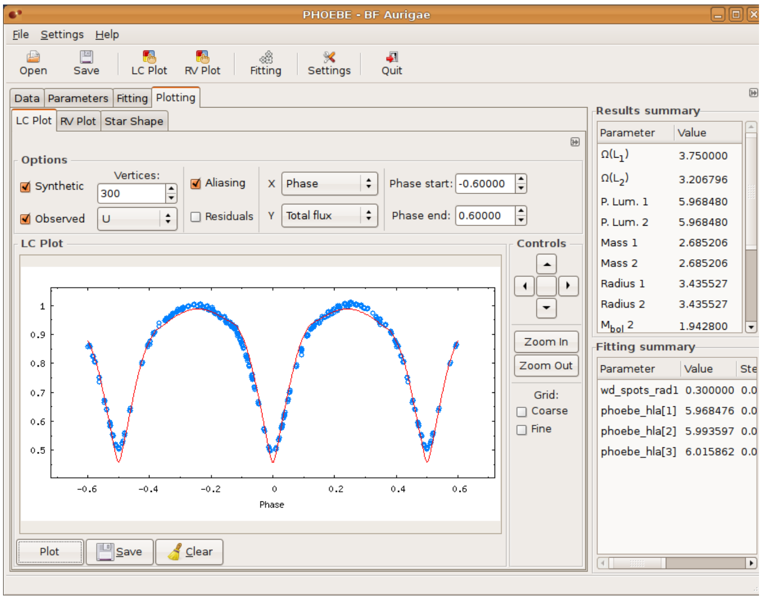

Figure 8: Program PHOEBE. Plotting tab – light curves, RV curves, and plane-of-sky star figures can be plotted here. The example shows a light curve plot [10].

5 Recent research

On 28 October 2010 article *A two-solar-mass neutron star measured using Shapiro delay* was published in International weekly journal of science. The Shapiro delay is the extra time delay light experiences by travelling past a massive object due to general relativistic time dilation. It was first verified by Irwin Shapiro in 1964. In binary pulsar systems that we see it nearly edge-on, excess delay in the pulse arrival times can be observed when the pulsar is situated nearly behind the companion during orbital conjunction. As described by general relativity, the two physical parameters that characterize the Shapiro delay are the companion mass and inclination angle [12].

The authors studied pulsar and its binary companion nearly edge-on. Pulsars are supernova remnants and there were discovered more then 1500 pulsars [4]. Pulsar is a rotating neutron star that have jets of particles moving almost at the speed of light streaming out above their magnetic poles [11]. These jets produce very powerful beams of light, that we can detect on Earth. A neutron star is about 20 km in diameter and has the mass of about 1.4 times that of our Sun, thus they are very dense. Its internal temperature is to 10^8 K and surface temperature around 10^6 K [4]. Composition and properties of neutron star are still theoretically uncertain [12]. Like we saw in previous chapters, we are able to measure mass and other parameters of a star when it is in a binary system. Some of the important parameters published in article are presented in the next table:

Parameters	Value
Pulsar's spin period	3.1508 ± 10^{-6} ms
Orbital period	8.6866 ± 10^{-10} d
Inclination	$89.17° \pm 0,02°$
Mass of pulsar	$1.97 \pm 0.04 M_\odot$
Mass of companion	$0.50 \pm 0.006 M_\odot$
Characteristic age	5.2 Gyr

These measurements are very accurate and a pulsar mass is by far the highest precisely measured neutron star mass determined so far [12]. Because the mass of pulsar is much more than it supposed to be, thus the density is higher and they can more precisely determine or rule out theoretical models of their composition.

In October 2009 an article: *Accurate masses and radii of normal stars: modern results and applications* was published. The authors identified 94 detached binaries containing 188 stars, consistent with the next criteria: they had to be a non-interacting system and their masses and radii can both be trusted to be accurate to better then 3% [13]. They searched the literature for such systems, examined and recomputed all data. For each system they determined distance, eccentricity, period and approximate age, and for most members also their rotational velocity, metal abundance, mass, radius, luminosity, magnitude and effective temperature [13]. The effective temperature is accurate to 2%, distance to 5% and age to 25 − 50% [13]. Later on it is revealed how the physical parameters effect stellar evolution.

Kepler satellite was launched in March 2009. The Kepler Mission is a NASA Discovery Program for detecting potentially life-supporting planets around other stars and determine how many of the billions of stars in our galaxy have such planets. This is done by photometry. Observations have already shown the presence of planets orbiting individual stars in multiple star systems [14]. The resolution needed to detect transit of the planet must be very high and Kepler telescope simultaneously measures the variations in the brightness of more than 100.000 stars every 30 minutes, so there is a lot of data to examine [14]. From these data certain physical parameters for eclipsing binaries can be extracted.

6 Conclusion

Double stars are unique because they allow measurements of mass stars, which is not identifiable in any other way, but it is a basic parameter which determines the evolution of individual stars. In addition, we provide measurements of the stellar radius of stars with great accuracy. As the temperature is easily measurable (like in single stars) by multiplying it with the luminosity we get distance to a star. A detailed understanding of the structure and evolution of stars requires knowledge of their physical characteristics. We have shown that eclipsing binaries play a special role in star research, because from their typical geometrical layout and well-understood physics we can extract a lot of information. From observation the stars we get data how the brightness changes over time and their radial velocities. From numerical models and PHOEBE programme we can accurately determine values of various physical parameters: mass and radii of both stars, inclination, eccentricity of the orbit, effective temperature, luminosity... Understanding binaries also helps us to understand wider universe: star evolution and because stars are main component part of galaxies, therefor helps us understand evolution of galaxies too.

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