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Faculty of Mathematics and Physics

DOCTORAL THESIS

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A study of binary stars with accretion disks

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Prohlašuji, že jsem tuto disertační práci vypracoval samostatně a výhradně s použitím citovaných pramenů, literatury a dalších odborných zdrojů.

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Title: A study of binary stars with accretion disks
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Abstract: This thesis contains spectroscopic analyses of two unusual binaries with circumstellar disks – β Lyr and ϵ Aur. Several hundred optical spectra were processed and analyzed for both binaries which led to several original findings. For β Lyr, it was a discovery of a weak shell spectrum originating in a disk pseudophotosphere and a hidden satellite spectrum, present only during eclipses, which arise from additional absorption of the primary light passing through the gaseous envelope around the secondary. For ϵ Aur, it led to the discovery of the apparent multiperiodic line variability occuring during the current eclipse with a dominant and common period of $66\overset{\mathrm{d}}{.}21$ and to an explanation of complex Hα line profiles during the eclipse which is again caused by an additional absorption of a primary light in an atmosphere of a dark disk around a secondary. Also rich series of radial velocity measurements and photometric observations were collected and used to determine a new precise orbital solution for ϵ Aur. Further, a hydrodynamical and a radiative modeling of a discontinuous mass transfer in a close binary system was carried out which resulted in a formation of an elongated disk with a slow prograde revolution, demonstrated itself by double emission Hα line profiles that exhibit V/R variations.
Keywords: stars: individual: β Lyr, ϵ Aur – stars: binaries: eclipsing – stars: emission-line – accretion disks

Název práce: Studium dvojhvězd s akrečními disky
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Abstrakt: Tato disertační práce obsahuje spektroskopické analýzy dvou neobvyklých dvojhvězd s diskem kolem jedné ze složek – β Lyr a ϵ Aur. Několik stovek optických spekter bylo zpracováno a analyzováno pro obě dvojhvězdy, což vedlo k několika původním výsledkům. Pro β Lyr jde o objev slabého spektra pocházejícího z pseudofotosféry disku a skrytého satelitního spektra, přítomného pouze během zákrytu, které je způsobeno dodatečnou absorpcí světla primáru procházejícího skrze plynou obálku kolem sekundáru. V případě ϵ Aur vedly analýzy k objevu zjevné multiperiodické proměnnosti spektrálních čar během zákrytu s hlavní společnou periodou $66\overset{\mathrm{d}}{.}21$ a dále k objasnění komplexních profilů čáry Hα během zákrytu, které jsou opět způsobeny dodatečnou absorpcí světla primáru v atmosféře tmavého disku okolo sekundáru. Pro ϵ Aur bylo též získáno velké množství měření radiálních rychlostí a fotometrických měření, které byly pouzity na výpočet nového přesného orbitálního řešení této dvojhvězdy. Dále pak bylo provedeno hydrodynamické a "zářivé" modelování diskrétního přenosu hmoty mezi složkami blízké dvojhvězdy, což vedlo k vytvoření eliptického disku s pomalou prográdní rotací. Profil Hα čáry vznikající v daném disku se pak vyznačovaly dvojitou emisí s nápadnými V/R změnami.
Klíčová slova: hvězdy: individiuální: β Lyr, ϵ Aur – hvězdy: dvojhvězdy: zákrytové – hvězdy: emisní čáry – akreční disky

Contents

1 Introduction

1.1 General remarks about binaries

One of the essential achievements of a "modern" astronomy is the discovery that many stars, although they appear as single stars to the naked eye, are indeed binary systems (or even multiple star systems). It is not easy to carry out any statistics about a ratio of single and multiple stars and a correlation of various parameters describing them since there are several selective factors that discriminate against some kinds of binaries from to be detected. For example, companions that are too close and/or too faint with respect to the other star. Therefore our sample of binaries among observed stars is still incomplete. However, there were already attempts to do such statistical analyses (see e.g. Abt 1983, and referencies herein). These statistical studies generally conclude that more than 50% of observed stars are in fact binary systems that may consist of virtually any combination of various stellar objects (from supergiants to black holes) and that their orbital periods may span from minutes to hundreds of years. Binary stars research is therefore a very wide and interesting branch of astronomy which is still very popular among an astronomical community. There are many lecture notes, publications and textbooks dealing with a basic or more detailed introduction and discussion of this field of astronomy (e.g. a good monograph by Hilditch 2001, or also author's master thesis). Here, I restrict myself only to some general facts about binaries with special regard to close binaries.

There is only a relatively small number of *visual binaries* which can be resolved as two separated stars, even using modern big telescopes. This generally arises because stellar distances are many orders of a magnitude higher than a "typical" separation of binary components. Therefore we can resolve only close binaries with a wide component separation which are not very valuable for a binary research due to their long periods, typically being of an order of hundreds of years. However, modern interferometers can now achieve orders of a magnitude better resolution than "classical" telescopes and so they are capable of resolving visual binaries with much shorter periods as was recently presented for example for σ^2 CrB which has an orbital period of $1\overset{\mathrm{d}}{.}14$ (Raghavan et al. 2009). From astrometric observations of visual binaries covering at least most of one orbital cycle, it is possible to derive reasonably accurate parameters of their relative elliptical orbits, including their inclination i. But the semi-major axis a of the elliptical orbit is derived only relatively to the system's distance d, i.e. only a factor a/d is derived from a solution. Finally, there are also so-called *astrometric binaries* which are single stars slightly changing their positions due to unseen orbiting companions. But astrometric binaries are from a certain point of view a subclass of visual binaries, only an absolute orbit instead of a relative orbit is observed.

Most of the known bright binaries are *spectroscopic binaries* which manifest themselves by an orbital motion of their components. A radial component of this orbital motion causes periodic Doppler displacements of spectral lines in their spectra. The spectral lines of both stars move in antiphase and in a simple periodic manner that defines *radial velocity curves.* The radial velocity curves can be expressed analytically using Kepler laws and by fitting to observed values of radial velocities, one can derive parameters of an absolute orbit of given binary. However, only expressions $a \sin i$ and $M_{1,2} \sin^3 i$ can be computed so it is possible to derive only lower limits for a semi-major axis a and masses of both stars $M_{1,2}$. In many cases, a flux difference between components is too high or amplitudes of the radial velocities are too low for a resolution of both components and only the radial velocities of one component can be measured. For such *single line spectroscopic binaries*, only $a_1 \sin i$, where a_1 is a semi-major axis of given component, and so-called *mass function* $f(M_{1,2}, i)$ can be derived. However, there are methods of a spectral disentangling implemented in several programs (see e.g. Simon & Sturm 1994; Hadrava 1995, 1997, 2004; Ilijic et al. 2004) which are able to separate spectral lines of components with the flux difference of several orders of magnitude and to derive parameters which can be obtained for classical *double line spectroscopic binaries*.

The last and very important class are *eclipsing binaries*. These are binaries whose orbital plane roughly intersects our solar system and therefore one can observe periodic variations of a binary brightness caused by the mutual eclipses of both components. Photometric observations during one orbital period define a *light curve* which typically has two different minima due to both eclipses during one orbital cycle. Analysis of their light curves is a complicated task since it is necessary to take into account various effects – e.g. partial eclipses caused by a low inclination, limb darkening of both stars, their nonspherical shape or mutual iradiation. There are several sophisticated programs for solving the light curves (see e.g. Wilson & Devinney 1971; Prša & Zwitter 2005) which generally use an analytical expression of an intensity as $I(r_{1,2}, i, e, q, T_{1,2}, ...)$ where $r_{1,2} = R_{1,2}/a$ are the relative radii of both stars, i is the inclination of an orbit, e is the orbital eccentricity, $q = M_2/M_1$ is the mass ratio and $T_{1,2}$ are temperatures of the stars. All parameters listed above can be derived by an appropriate light curve solution. A complication is that it is possible to get only relative radii of stars, not absolute ones. For completeness, it should be said that there are also eclipsing binaries for which only one eclipse is observed. It could be caused either by an enormous difference in a brightness of the stars (in a wavelength range of given photometric observations) or by a factual nonexistence of the second eclipse for binaries in a highly eccentric orbit.

The spectroscopic binaries which are also observed as the eclipsing systems play an important role in the development of a stellar astrophysics. The analysis of their light curves gives the inclination which can be used for a radial velocity solution to get values of a semi-major axis and both stellar masses. A value of the semi-major axis can be reversely used in a light curve solution to determine absolute radii of both stars. Therefore eclipsing binaries are in fact the most accurate source of our knowledge of stellar masses, radii and temperatures. Moreover, from a knowledge of radii and temperatures of both stars, it is possible to compute a total flux of the binary which can be used to derive a distance of the system. This method of a distance determination is very accurate and appropriate to calibrate other methods for the distance determination. Moreover, the eclipsing binaries discovered in nearby galaxies helped us determine their distances very accurately (Kaluzny et al. 1998). Similarly, the spectroscopic binaries resolved also as the visual ones and observed astrometrically for a reasonably long time are also important. Again, the visual binaries give us an inclination which can be used to determine a semi-major axis and the masses of both stars. A value of the main semi-major axis can be reversely used get a distance of the system since visual "solution" gives an angular "separation", i.e. a term a/d. When temperatures are determined for both stars indirectly (e.g. from color indices or spectroscopic anayses), it is possible to estimate stellar radii.

Besides accurate distance and stellar parameters determinations, there are also several other important aspects of binary stars. It is generally believed that binary components originate at the same time and from the same protostellar material and therefore have the same age and chemical composition. This implies that theories of a stellar evolution can be tested by a comparison of evolution stages of binary components. Also stellar interior can be studied via an apsidal motion of a component orbit for well suited eccentric eclipsing binaries. And finally, methods developed for a binary stars research have been directly extrapolated for searching and the parameters determination of extrasolar planets. The study of extrasolar planets is now possibly the most active field of astronomical research since it can lead to "a holy grail of astronomy" – the discovery of Earth-size planets that could be suitable for life in our Galaxy.

There is also another widely used classification of binary systems especially related to close binaries – a classification with respect to a dynamical stability of the components. Any matter in a vicinity of a binary system is influenced by three main forces: gravitational forces of both stars and the centrifugal force due to an orbital motion of the system. These three forces are a base of so-called *Roche potential*, which was first successfully applied to interpret a close binary β Lyr (Kuiper 1941) and its theory with respect of the close binaries was largely developed by a Czech astronomer Dr. Zdeněk Kopal. Discussions of the Roche potential are presented in many publications (see e.g. Hilditch 2001) and it is not necessary to repeat it here. The most important fact is that the first equipotential surface which is common for both stars, so-called *critical Roche equipotential*, has a shape of a number 8 in an orbital projection with a relative size of both lobes dependent only on a mass ratio q. The close binaries are then classified according the position of star's "surfaces" with respect to the critical potential - detached binaries consist of both stars within their respective critical lobes, semidetached binaries contain one star which exactly fills its critical lobe and in contact binaries, both stars fill or even exceed their critical lobes and therefore such a system has a common envelope.

Evolutionary models of single stars are already highly developed (see e.g. Schaller et al. 1992). Therefore it is well known that stars change their radii during their evolution and that the most prominent increase of the stellar radius takes place when a nuclear fusion of hydrogen begins in layers above a core of the star and the star leaves the main sequence and rapidly evolves to a giant stage. If such a star is a component of a close binary then its surface can reach the critical potential and the gas which exceeds so-called *first Lagrange point* (defined as an "intersection" of both lobes forming the critical potential) is transferred to a companion. The stars begin to interact and their discrete "single star" evolution is disturbed. The evolution of the star filling its critical lobe can be computed (after several simplifying assumptions) as an evolution of a single star losing discretely a certain amount of the mass from its surface between two consequent time iterations of its stellar structure. This method was introduced and first applied by Kippenhahn & Weigert (1967). Harmanec (1970) provided detailed structural models of two mass losing stars with different masses. A review of other model sequences of mass lossing stars can be found in Paczyński (1971). An essential result of these models is an explanation of so-called *evolutional paradox of interacting binaries* which was based on a question why mass losing stars in interacting binaries generally have a lower mass then their companions when it is well known that more massive stars leave the main sequence first. These models reveal that the mass transfer rate is very high during the initial stages of the interaction and it soon leads to the reversal mass ratio of components.

A reasonable modeling of the mass transfer between components itself is a very complicated task. It generally requires using of three-dimensional hydrodynamical numerical modeling which is not easy to implement correctly and mainly, such precise simulations place very high demands on computer capacities. Such modeling are done, for example, by a Moscow group led by Dr. Dmitrij V. Bisikalo (see e.g. Bisikalo et al. 2000). These simulations provide a confirmation of what was generally assumed about a nature of the mass transfer between components. The mass flowing from the first Lagrange point forms a concentrated stream which is deflected by the Coriolis force (due to the orbital motion of the system) to the direction of the orbital motion of the mass loosing star, then this gas circles the second star and intricately interacts with the former stream. Most of the matter then forms so-called *accretion disk* – a disk-like structure of a dense matter which orbits around the secondary and slowly accretes on its surface. Some gas can also form another circumstellar structures like a spherical envelope around the secondary or jets that are perpendicular to an orbital plane and originate in a place of a stream-disk interaction. A significant amount of the matter also escapes from the system entirely and decreases the total mass and an angular momentum of the system. The presence of accretion disks and other circumstellar structures significantly affects observations of binary systems. Therefore some objects can not be explained by a "classical" binary model consisting only from two stars orbiting around each other. The theory of the mass transfer in the close binaries introduced the accretion disks and other circumstellar structures which help solve mysteries of some unusual binaries. One of these binaries is indeed β Lyr whose spectral analysis forms one part of this thesis.

1.2 A review of my papers related to binaries with disks

This PhD thesis is based on four papers accepted and published (mostly) in peer-reviewed and scientifically high-impacted journals. A list of the papers follows – "New findings supporting the presence of a thick disc and bipolar jets in the β Lyrae system" (Ak et al. 2007, published in A&A), "A new ephemeris and an orbital solution of ϵ Aurigae" (Chadima et al. 2010, published in IBVS), "Spectral and photometric analysis of the eclipsing binary ϵ Aurigae prior to and during the 2009–2011 eclipse" (Chadima et al. 2011b, accepted for a publication in A&A) and "Hydrodynamical and radiative modeling of temporal Hα emission V/R variations caused by a discontinuous mass transfer in binaries" (Chadima et al. 2011a, accepted for a publication in AJ). Since these papers make up a core of this thesis, my contribution on their preparation and on analyses presented in them should be clearly specified.

Generally, I can declare that almost all analyses presented in given papers were done by myself (exceptions are discussed below). Here, my supervisor, Dr. Petr Harmanec, should be credited for his regular consultations and valuable suggestions and advice and for the particular support with some analyses which helped me greatly in reaching scientific results presented in the papers. Therefore he is mostly listed just after me in lists of coauthors. Almost all other coauthors of these papers contributed a large amount of photometric and spectroscopic data used for given analyses. A calibration and a rectification of all spectra (except an initial reduction of all Ondřejov spectra) and consequent measurements on them were carried out by me. The content of all papers was written initially by me and then critically reviewed and partly edited by my supervisor before being submitted to particular journals. I was also a corresponding author of all papers who communicated with other coauthors and also with editors and referees during submitting processes. Some comments to particular papers follow.

A spectral analysis of the β Lyr system (Ak et al. 2007) is the only paper where I am not listed as the first author, but as the second author. It is related to the fact that the first author Dr. Hasan Ak was the first who reduced and measured available spectra and attempted to do analyses presented in Sect. 4 and Sect. 5. I was motivated by his work and discussed several related things with him. Nevertheless, I did whole analyses again and more precisely using a larger amount of spectra which

I reduced and measured by myself. I also wrote the text of the paper and submitted it. However, I finally decided to present Dr. Hasan Ak as the main author of the paper because of his initial measurements and analyses made on the spectra and our valuable discussions. Next, I should admit that a large amount of the work on β Lyr was done and presented already in my master thesis. However, at the beginning of my PhD studies, I redid most of the analyses in a better way (e.g. all spectra were recalibrated using telluric lines before a new disentangling), added new analyses presented in Sect. 6, wrote the whole paper and supervised the submitting process. Therefore I find it fully justified to present this paper as a part of my PhD thesis.

A new ephemeris and an orbital solution of ϵ Aur (Chadima et al. 2010) is the only paper which was not published in an high-impacted scientific journal, although I personally believe that it would easily be accepted in such a journal. Initially, this work was intended to be submitted in A&A but the acquisition of all accessible radial velocities and photometry took me a long time. Because of the current eclipse had already been in progress and also due to an announcement of an independent orbital solution of ϵ Aur (Stefanik et al. 2010), I decided to publish our orbital solution and a resulting prediction of a mid-eclipse date as quickly as possible. This is why I submitted it to IBVS which ensured a fast publication.

In the case of the second paper regarding ϵ Aur (Chadima et al. 2011b), I would like to acknowledge two people (in adition to my supervisor) – Dr. Viktor Votruba for a preparation of synthetic spectra used for a comparison in Sect. 3 and Dr. Philip Bennett for his very valuable comments regarding an "Introduction" of the paper and a comparison of synthetic and observed spectra and also for his editing of this particular part of the text.

The last paper about a modeling of V/R variations (Chadima et al. 2011a) is the only paper which is focused on a theoretical modeling instead of analyses of observed data. Dr. Roman Fiřt should be credited here for carrying out the hydrodynamical modeling presented in the paper and for writing an initial draft of Sect. 2. However, I discussed the given simulations and appropriate initial parameters with him. Dr. Roman Fiřt did this part of given analysis because he was familiar with the use of a sophisticated program designated for three-dimensional hydrodynamical computations – ZEUS from his own field of a research. Afterwards, I made radiative transfer computations and then completed and submitted the paper for publication.

2 Beta Lyrae

β Lyr is a bright star ($V_{max} = 3\overset{m}{.}34$) in a constellation of Lyra. Its equatorial coordinates are $\alpha = 18^{\rm h}50^{\rm m}05^{\rm s}$, $\delta = 33°21'46''$ (for epoch 2000.0) and a Hipparcos distance was estimated to (270±30)pc (Perryman & ESA 1997). It is a spectroscopic and eclipsing binary which has challenged many generations of astronomers because its observations could not be interpreted consistently. Nowadays, we know that this was caused by a fact that this system is at the end of a rapid mass exchange between components and therefore contains an accretion disk and other circumstellar structures which highly affect observed data. There are several good review papers describing the history of an investigation of β Lyr (see e.g. Sahade 1980; Harmanec 2002). Here, I would only like to summarize briefly some important studies of this system.

Goodricke & Englefield (1785) were the first who announced that β Lyr is a variable star with a period about 13 days. It was the second known variable star after β Per discovered also by John Goodricke in 1783. He already suggested that the periodic variability may be caused by eclipses by a dark companion. Argelander (1859) collected a large amount of photovisual observations and reported that the period is increasing in a rate of about 19 seconds per year (which is consistent with a current theory about a mass transfer in the system).

Secchi (1867) reported his visual spectroscopic observations and announced a discovery of an Hβ emission in the spectra of β Lyr which became the very first Be star known. Belopolsky (1897), who already used a photographic wavelength calibrated spectra, measured radial velocities of the Hβ emission and discovered that these line emissions varied at antiphase with respect to prominent absorption lines. He concluded that the emission comes from a companion and thus β Lyr is a binary. However, Curtis (1911) concluded that the emission originates rather in a gas envelope around the whole system. Consecutive attempts to find spectral lines of the companion failed but they revealed that the β Lyr spectrum is very complex and that it consists of six sets of spectral lines (Harmanec 2002).

It is useful to note that during the first half of the 19th century, astronomers fully believed in a validity of so-called *mass-luminosity law*, i.e. a relation $L \sim M^{\alpha}$ where L is a luminosity and M a mass of a particular star and α an empirical exponent. From a shape of a light curve, it was believed that the primary is brighter of the two and therefore also more massive (a mass ratio was not known due to an absence of the secondary lines). However, a mass function gave unrealistically high masses for both stars. For example, Kuiper (1941) adopted masses of 78 $M_{\odot}$ and 52 $M_{\odot}$ for the β Lyr components. Nevertheless, this study was very important since Kuiper (1941) was the first who considered the mass transfer between the components. He discussed the Roche potential applied to the β Lyr system in detail and also tried to explain an observed increase of the orbital period as caused by the mass transfer. This explanation was fully correct but since he assumed a reversal mass ratio, he got an enigmatic paradox.

Later, astronomers slowly revised their uncritical belief in a validity of the mass-luminosity relation and Gaposchkin (1956) was the first who introduced an idea that the secondary is hidden in dense structures of a circumstellar matter and is more massive from both components. This idea was further developed in an important study of Huang (1963) who suggested that β Lyr contains an accretion disk created by the transferred matter and that the disk hides the more massive secondary from a view. He also pointed out that an existence of a disk can explain a longer duration of the eclipses.

A very important contribution to the β Lyr research was done by Skulsky & Topilskaya (1991) who used high dispersion spectra to measure radial velocities of two weak silicon lines (first reported by Skulsky (1975)) and found out that they are in an exact antiphase to the radial velocities of the primary. Therefore they attributed these lines to the secondary, derived the mass ratio of the system and concluded that the secondary is the more massive star with a probable spectral type A5III. Harmanec (1992) concluded that these lines are rather shell lines of a disk pseudophotosphere but he agreed that they properly describe an orbital motion of the secondary. A year later, Harmanec & Scholz (1993) analyzed a rich collection of the radial velocities of both components and derived an accurate quadratic ephemeris of the system. They also pointed out that in the case of β Lyr, the ephemeris derived from the radial velocities is more precise then that derived from a light curve solution.

An indirect proof of the mass transfer in the β Lyr system was carried out by Balachandran et al. (1986) who analyzed the spectra in the aim to derive a chemical composition of the primary and they concluded that it corresponds to a spectral type B6II. But they realized that there is a high overabundance of several elements (viz.: nitrogen, carbon and oxygen) whose abundances are sufficiently close to equilibrium ratios expected from the CNO cycle. They interpreted this as a consequence of the mass transfer which brought deeper layers enriched by thermonuclear reactions to a surface of the primary. De Greve & Linnell (1994) attempted to calculate sequences of evolutionary models of the β Lyr system during the stage of a rapid mass transfer between the components and tried to establish a model of the system before the mass transfer stage. They concluded that initially, β Lyr consisted of two well separated stars and with a reversal mass ratio, its mass transfer was partly non-conservative (i.e. significant mass and angular momentum were lost from the system) and now it is at the end of the stage of the rapid mass transfer. These simulations also confirmed the conclusion of Balachandran et al. (1986) about the CNO processed elements overabundances found in the spectra.

There were several attempts to model the accretion disk and other structures of the circumstellar matter with the aim to sufficiently fit both the light curves and the spectra at various wavelengths during last decades. These theoretical models, whose general development was highly motivated right because of an endeavor to solve "mysteries" about β Lyr, brought a new light to a structure of the system. Wilson (1974) presented the very first model simulating the disk as a highly rotationally broadened star and demonstrated that the light curve can not be reasonably modeled without a presence of the disk in the system. Hubený & Plavec (1991) used a new disk model which the vertical structure was calculated from analytical equations. They concluded that most of the radiation comes from a disk rim. Linnell & Hubený (1996) used a program BINSYN (which is able to fit light curves and spectra of binaries containing accretion disks) to β Lyr but they did not find any plausible solution of the light curve and the continuum energy distribution. Therefore they suggested a presence of a scattering envelope around the secondary. Such a scattering envelope was added to models made by Linnell (2000, 2002) who showed that the scattering envelope is necessary for a reasonable solution and also pointed out that the disk rim can not be isothermal but it should have some vertical distribution of a temperature. Bisikalo et al. (2000) and Nazarenko & Glazunova (2006) computed three-dimensional hydrodynamical models of the mass transfer between the components. These models led to a formation of all circumstellar structures expected in the system - the accretion disk, the spherical envelope and the jets (see the next paragraph).

Since β Lyr is in a vicinity of the Sun, there were already several attempts to resolve the system interferometrically. The first attempt was already done by Harmanec et al. (1996) as a part of a big international observing campaign of β Lyr. The binary itself was not resolved which was most probably caused by a fact that the binary orientation on the sky was roughly perpendicular to a baseline of an interferometer used. However, the Hα emission was partly resolved and it led to a conclusion that it originates in jet-like structures perpendicular to an orbital plane which are probably emitted from a place of an interaction of the disk and the former stream of a matter from the primary. This conclusion was latter confirmed by hydrodynamical simulations (Bisikalo et al. 2000; Nazarenko & Glazunova 2006) as was already mentioned in the last paragraph. The next attempt to resolve the Hα emission was done by Schmitt et al. (2009) but the jets were not detected in this case which may be caused by a limited resolution in a direction perpendicular to the orbital plane. A remarkable attempt for the interferometric resolution was done by Zhao et al. (2008) who got images of the system (at several phases) with the disk and the elongated primary which was declared as the first direct detection of a stellar distortion due to its Roche lobe filling.

Finally, I would like to summarize the currently accepted model for β Lyr which is described for example by Harmanec (2002). β Lyr is an eclipsing binary with a current period of $12\overset{\mathrm{d}}{.}94$ and an orbital inclination of $i = 86°$. The primary is the B6-8II star with a mass of $\sim$3 $M_\odot$, a radius of $\sim$14.5 $R_\odot$ and a temperature of $\sim$13,000 K. The unseen secondary is believed to be an early main sequence B star with a mass of $\sim$13 $M_\odot$, a radius of $\sim$6 $R_\odot$ and a temperature of $\sim$28,000 K. A separation of the components is $\sim$58.5 $R_\odot$ and there is a mass transfer between them with a rate of about $\sim$2 x 10^{-5} $M_\odot$ yr^{-1}. The mass transfer creates an optically and geometrically thick disk around the secondary with a radius of $\sim$30 $R_\odot$, a rim semithickness of $\sim$8 $R_\odot$ and a rim temperature about $\sim$9,000 K. Other circumstellar structures are a scattering envelope around the secondary and jets perpendicular to the orbital plane which are a source of the prominent emission seen in the spectra of β Lyr.

2.1 A spectral analysis of beta Lyrae

Our spectral analysis of β Lyr (Ak et al. 2007) is based on three sets of spectra. A short description follows: 1) 52 photographic spectra (later digitalized) secured during 1991 with the 2-m reflector at the Ondřejov Observatory and covering two overlapping regions 3630–4550 Å and 4060–5000 Å, 2) 275 CCD spectra secured between 1992 and 2003 again in Ondřejov and covering the region from 6280 Å to 6730 Å and 3) 376 CCD spectra secured from 1994 to 2003 using the 1.22-m reflector at the Dominion Astrophysical Observatory and covering a wavelength range of 6150–6760 Å. We also had 255 UBV photometric observations at our disposal (62 from the Hvar Observatory and 193 from the Tubitak National Observatory) which were used for a light curve modeling (for a purpose of a spectral correction mentioned below).

The last ephemeris of β Lyr was calculated by Harmanec & Scholz (1993). It was a quadratic ephemeris because a period is slowly increasing due to a continuing mass transfer between components and it was found that the quadratic ephemeris is sufficient to an accurate description of a binary orbit. Since we had several hundred more radial velocity measurements from next ten years from our spectra, we decided to derive an improved quadratic ephemeris of the system. Our results do not differ significantly from the ephemeris by Harmanec & Scholz (1993) which attested to the accuracy of the old quadratic ephemeris.

Since β Lyr is a single line spectroscopic binary, we decided to use our rich collection of the spectra in an attempt to apply a spectral disentangling to them. We used a program KOREL, developed by Hadrava (1995, 1997, 2004) and several limited spectral regions (especially on photographic spectra) carefully chosen to contain many stellar lines but no interstellar or circumstellar lines. We chose an appropriate method of the disentangling process (described in the paper) and we succeeded in detecting a weak secondary spectrum at all wavelength regions which we attributed as the spectrum originating in a pseudophotosphere of a thick disk around an unseen secondary star. This was the first detection of this spectrum, except to previously known SiII6347 and SiII6371 lines reported already by Skulsky (1975). We also carried out a comparison of disentangled spectra with synthetic spectra and concluded that the primary spectrum corresponds quite well to the synthetic spectrum with T = 13,000 K, log g = 2.5[cgs] and $v \sin i$ = 55 km s^{-1}, which agrees with values currently adopted for this star. A similar comparison for the secondary spectrum is very complicated but we conclude that the most appropriate rotational velocity agrees well with the expected Keplerian rotation of the outer parts of the disk.

We measured a central intensity and an equivalent width of 15 prominent absorption lines of the primary and corrected these values for the light curve of the system using correction equations presented and discussed in the paper. The light curve solution, necessary for doing given correction, was computed by a program BINSYN developed by Linnell & Hubený (1996) since this program is capable to solve light curves of systems containing accretion disks. The correction for the light curve revealed that all metallic lines undergo a very prominent increase of their strength during primary eclipses. Several possible explanations of this phenomen failed and therefore we concluded that this is an indirect detection of a new satellite spectrum caused by an absorption of a primary light in circumstellar structures surrounding the secondary, i.e. in one of jets and a scattering envelope.

Finally, we measured a central intensity of V and R peaks of the Hα line and did again the correction for the light curve but in this case, a different one that assumes that this emission arises from the orbital plane and therefore it is not affected by stellar eclipses. After applying this correction, the pronounced orbital variations of the central intensity of both peaks almost disappeared. This is an indirect proof that the emission indeed originates outside of the orbital plane. This strongly supports a hypothesis made by Harmanec et al. (1996) that the emission originates in jet-like structures perpendicular to the orbital plane. A period analysis applied to these corrected values did not find any non-orbital period of a statistical significance.

3 Epsilon Aurigae

ϵ Aur is a bright star in a constellation of Auriga ($V_{max} = 3^{\mathrm{m}}.04$, $\alpha = 05^{\mathrm{h}}01^{\mathrm{m}}58^{\mathrm{s}}$, $\delta = 43°49'24''$, for epoch 2000.0). It is a single line eclipsing binary with the longest known orbital period of 27.1 years and a long duration of a primary eclipse of almost 2 years. A confirmed detection of a secondary eclipse has never been reported. This enigmatic system, which is still not fully understood, has attracted an interest of several generations of astronomers and a list of publications on this topic is very extensive. There is a good review paper by Guinan & Dewarf (2002) which discusses currently accepted models of the system with respect to a related theoretical and an observational background. Here, I would like to restrict only to some important papers and interpretations of ϵ Aur.

Johann Fritsch in 1821 was the first who reported (in a letter to a colleague) that ϵ Aur was variable. An eclipse of ϵ Aur occurred in that year and so it was much dimmer ($\sim 4^{\mathrm{m}}.0$) when compared with nearby stars. But this report did not attract any attention. The next eclipse in 1847[1] was observed and reported by Eduard Heis and Friedrich Wilhelm Argelander. ϵ Aur was interpreted as an irregular variable and became to be a regular observing target. Ludendorff (1903, 1912) collected the rich and long-term series of photovisual observations of the star and from their analysis, he concluded that ϵ Aur is an eclipsing binary with a very long period of about 27 years. Each next eclipse was therefore a rare occasion which attracted more and more observers and a highly increasing amount of data was secured during them. It should be noted here that during the last eclipse in 1983, a disputable increase in brightness close to a mid-eclipse (called as a *central brightening*) was reported (Stencel 1985). Although this phenomen was not definetely confirmed by observations neither during previous eclipses nor during the current eclipse in 2010, it had a significant influence on the interpretation of the system (as discussed below).

Even more notable than the long orbital period is the long duration of the eclipses which (in a combination with a large binary separation) means that an eclipsing object must be huge. The eclipses are flat-bottomed which is a classical indication that it is a total occultation. But a spectrum of the system which almost exclusively belongs to the star being eclipsed remains almost unaltered during the eclipses. Therefore we are challenged with a huge object causing partial eclipses which does not emit enough radiation to be observed. The first hypothesis was introduced by Kuiper et al. (1937) who proposed that the eclipsing object is a huge extremely cool tenuous star which is partially transparent. Struve (1956) proposed that the eclipsing object consists of a cool central star which is surrounded by a spherical semitransparent envelope filling a whole Roche lobe. Huang (1965) already introduced a model where the eclipsing object was a thick cool disk which covered about a half of the visible star during the eclipses. Wilson & Devinney (1971) suggested that the disk is thin but it is slightly tilted with respect to an orbital plane of the system. Carroll et al. (1991) tried to fit a light curve, including the central brightening already mentioned, and concluded that the disk has a central hole and the semitransparent central regions. This model was proved also by Ferluga (1990) who obtained a good fit using a model of the disk (with a central hole) consisting of concentric rings of a various transparency. Backman et al. (1984) were first to detect a radiation from the disk as an excess in infrared wavelengths and determined its temperature to about ~500K. However, the first direct observation of the disk was made by Kloppenborg et al. (2010) using an optical interferometry during the current eclipse which revealed the

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[1] Since the eclipses last almost two years, I denote them by the year of a corresponding mid-eclipse for simplicity.

visible star being half-obscured by a very elongated dark object.

Morris (1962) made an orbital solution of the system and derived a mass function $f(m)$ of this single line spectroscopic binary as $f(m) = 3.12\ \mathrm{M}_{\odot}$. Since an orbital inclination is known, it is only necessary to determine a mass of the primary star to get a complete solution of the system. Carroll et al. (1991) considered from spectroscopic analyses that the primary is a F0Ia star and assigned it a mass 15 $\mathrm{M}_{\odot}$ which is typical for these stars. They derived that the unseen secondary should have a mass about 13 $\mathrm{M}_{\odot}$ and that a semi-major axis should be about 27.6 AU. They assumed a radius of the primary from stellar models to be about 200 $\mathrm{R}_{\odot}$ and derived a radius of the disk (from a light curve analysis) to be about 2000 $\mathrm{R}_{\odot}$. Their model, which is now called a *high-mass model*, was presented and discussed by Carroll et al. (1991, see Fig. 6). The primary in this model lies well inside its Roche lobe and it is highly improbable that there was any mass transfer to the secondary which could form the pronounced disk around it. Therefore this disk should be of a protostellar/protoplanetary origin as suggested already by Kopal (1971). There is an evidence of such disks around several other stars, for example around β Pic (Smith & Terrile 1984). These disks are typically larger than that in the ϵ Aur system but it is probable that the disk was truncated and limited to its current size by a presence of the critical Roche lobe. Moreover, it was estimated from an evolutionary stage of the primary that the system has an age of about 10^7 years and it is known that there are still protoplanetary disks around stars which are at least the same age (Strom et al. 1989).

The main problem which arose with the high-mass interpretation of the system was a fact that there should be a 13 $\mathrm{M}_{\odot}$ object in a disk center but it was not observed at any wavelength. If it is a main sequence star, it should be easily observable. Therefore there is a question about a nature of this massive object which remained undetected. Lissauer & Backman (1984) suggested that it can be a close binary. They showed that if the mass 13 $\mathrm{M}_{\odot}$ is equally distributed between the components than a luminosity of the system would be about 10% of the luminosity of the single star if the same mass. Moreover, an evolution of less massive stars is slower and so both objects can still be in a stage of protostars which would be even much less luminous. However, Bennett et al. (2005) modeled a far ultraviolet emission spectrum of ϵ Aur and from the best fit, they concluded that a continuum radiation of the secondary is scattered by a strong wind of the primary and that the hidden object inside the disk should be a main sequence B5 star. Another solution (but early) of the luminosity problem was presented by Cameron (1971) who suggested that the secondary is a black hole. This was an interesting possibility and ϵ Aur was then observed in far ultraviolet and X-ray wavelengths several times to detect a radiation from a matter accreting into the hypothetical black hole (see e.g. Wolk et al. 2010) but no such radiation was observed. However, it is possible that there is no accretion, which could produce high energy radiation, occurring in the system currently or that this radiation is scattered out of the orbital plane by the dense disk and therefore it is undetectable from the Earth.

In an attempt to solve the luminosity problem, Eggleton & Pringle (1985) introduced a new model which is now called a *low-mass model*. They proposed that the primary is in fact an old star, already evolved to a post-AGB object, which only seems to be an F supergiant. They suggested its mass to ∼1 $\mathrm{M}_{\odot}$ which led to rescaling of all other parameters of the system with respect to the known mass function. The low-mass model would therefore consist of the ∼1 $\mathrm{M}_{\odot}$ primary, the ∼4 $\mathrm{M}_{\odot}$ secondary with a semi-major axis of ∼17 AU. The binary scenario is also possible for this model. The disk should have a radius of ∼7 AU and it was formed by a recent accretion when the primary filled its Roche lobe.

There are still no firm constrains that can determine which model (the high-mass or the low-mass) is correct. The direct method how to resolve between both models would be to derive an accurate distance to the system since the high-mass model should have in orders of a magnitude a higher absolute magnitude than the low-mass model. Unfortunately, the current distance estimates from a Hipparcos parallax (Perryman & ESA 1997; van Leeuwen 2007) have so high errors (due to a very small parallax of the system) that it covers both models. Since known post-AGB objects have large changes in brightness and temperature on time scales of decades (see e.g. Herbig & Boyarchuk 1968), Guinan & Dewarf (2002) tried to examine several old stellar catalogues from Almagest by Ptolemy (about 130 B.C.) till today to find any changes in brightness. Although old magnitude estimates are not very precise, they concluded that there was probably no prominent variation in brightness (greater than $\sim 1^{\mathrm{m}}.0$) of ϵ Aur during two last millennia. But it is possible that the brightness change was missed or occurred before the examined period. Hoard et al. (2010) combined several spectral observations and obtained a spectral energy distribution from $\sim$0.1 μm to 100 μm. They reproduced it by a model consisting of three components – a 2.2 $M_\odot$ F type post-AGB star, a 5.9 $M_\odot$ B5V star and a geometrically thick but partly transparent disk of gas and dust with an effective temperature of $\sim$550 K. From this study, they claimed that the low-mass model is correct. But this model disagrees with a far ultraviolet spectral analysis made by Bennett et al. (2005) who concluded that there is only an emission line spectrum most probably caused by a scattered light from the B5V secondary. On the other hand, this model serves rather as a proof in favor of the high-mass model. Recently Sadakane et al. (2010) carried out a detailed abundance analysis of the ϵ Aur spectra and they concluded that there is no evidence for the post-AGB object and the primary seems to be a normal F type supergiant.

Finally, I would like to present my opinion about the model of ϵ Aur. Personally, I prefer the high-mass model since it generally seems to be more consistent than the low-mass model. The high-mass model was naturally constructed from an analysis of the primary spectrum and from the known mass function but the low-mass model was later suggested only because of the luminous problem discussed above. But if we assume that the disputable central brightening is not a real effect but a consequence of the intrinsic variability of the primary or inaccurate observations made in a very high air mass (as was shown by Chadima et al. (2010)), then there is no need of a central hole in a tilted thin disk. Therefore the central object can be fully obscured by the disk and a very high degree of scattering of its light out of the orbital plane makes it directly unobservable. The only evidence of a luminous star in the center of the disk is the scattered light seen in the far ultraviolet region as was presented by Bennett et al. (2005). This gives a natural explanation for the luminosity problem and makes the high-mass model to be consistent in all main points of view. In that case, there is no need to introduce an alternative model which has several inconsistencies.

3.1 A new orbital solution of epsilon Aurigae

It is not easy to secure an accurate ephemeris and an orbital solution for ϵ Aur. There are two main reasons for this. First, ϵ Aur is a long-period binary and it is necessary to observe this star for 27 years to cover only one cycle of its orbit which can be taken as a reasonable minimum for any orbital solution. Second, a scattering of both the radial velocities and the photometric observations is very high and so it is complicated to do a good fit of both the radial velocity curves and the light curves. For completeness, it should be mentioned that there no secondary minimum is observed which is also a certain complication for any orbital solution. Therefore for a precise orbital solution, it is necessary to accumulate a very large amount of photometric and radial velocity data from an interval of many tens of years.

The last orbital solution of ϵ Aur had been done by Wright (1970) forty years ago. Therefore we calculated an updated and more precise solution (Chadima et al. 2010). First, we tried to accumulate as many (historic) radial velocities and photometric observations as possible. We searched through several databases and consulted old papers dealing with ϵ Aur. It was possible to download some data from online sources but some data were only in a tabular form and it was necessary to manually type them to data files. We collected 759 radial velocity measurements and 542 photometric observations from various sources. It was completed by our own measurements which consisted of 208 radial velocities and 149 photometric observations. Finally, we received permission from Dr. Robert Stefanik to add their 515 radial velocities presented in their new orbital solution (Stefanik et al. 2010), announced only few days before an intended submission of our paper to the same topic. Altogether, we accumulated a total amount of 1265 radial velocities since the year 1899 and 908 photometric observations since the year 1848 (a journal of all data used and a short discussion of the new data is given in the paper). We should note that we used only radial velocity data outside of eclipses (due to a possible blending of lines during eclipses) and photometric observations during eclipses (they were exclusively used for determining a precise ephemeris). Also several sets of photovisual observations were removed for their high scattering.

We used two independent programs to derive a new ephemeris and an orbital solution – PHOEBE (Prša & Zwitter 2005) and FOTEL (Hadrava 1990, 2004). We realized that an ephemeris (i.e. a period P and an epoch of a primary mid-eclipse $T_{prim.mim.}$) can be much more accurately determined from the light curve solution and therefore we used the photometric data to calculate the period and the epoch and kept other orbital parameters fixed. However, we should emphasize that it was only a *formal* light curve solution calculated only in the aim to get the precise ephemeris, not to answer a question about a structure of the ϵ Aur system. On the other hand, a radial velocity curve fitting can get accurate values of an orbital eccentricity e, a longitude of a periastron ω and a radial velocity semiamplitude of the primary K_1 and so we used the radial velocity measurements to derive these parameters. By a separate solving of the light curve and the radial velocity curve, we iteratively derived the final ephemeris and the orbital solution for both programs.

Our orbital parameters are summarized along with parameters derived by Wright (1970) and Stefanik et al. (2010) (see Tab. 3 in Chadima et al. 2010) and compared with them. Our solution differs significantly from that of Wright (1970) and is much accurate due to using the longer time baseline covered by the data and not deriving the ephemeris from the highly scattered radial velocities. We are also convinced that our solution is more precise than that of Stefanik et al. (2010), not just because we also use their rich set of radial velocities, but since they solved the light curve and the radial velocity curve simultaneously (i.e. not separately as we did). We should also point out that an indirect proof of an accuracy of our solution is that all parameters derived by two independent programs are consistent within their errors.

From an inspection of all data at our disposal, we also arrived at two conclusions that disagree with generally accepted facts about ϵ Aur. We disputed a widely accepted reality of a central brightening during a mid-eclipse interpreted as an evidence of a hole in the disk (see e.g. Carroll et al. 1991) and suggest that the effect observed during the last (and partly during the before last eclipse) is rather caused by an intrinsic photometric variability of the primary. The photometric variability of the primary can also explain an observed fact of a variability in a width and a duration of individual observed eclipses which was initially interpreted as rapid changes of a primary radius (Saito & Kitamura 1986).

3.2 A spectral analysis of epsilon Aurigae

Our spectral analysis of a challenging eclipsing binary ϵ Aur (Chadima et al. 2011a) is based on three sets of spectra which short description follows: 1) 105 CCD spectra secured with the 1-22m telescope at the Dominion Astrophysical Observatory between the years 1994–2010 and covering a wavelength range 6200–6750 Å, 2) 201 CCD spectra secured using the 2-m telescope at the Ondřejov Observatory during 2006–2010 and covering a region from 6260 to 6760 Å and 3) 47 CCD spectra obtained with the 0.28-m Celestron telescope at the Castanet-Tolosan Observatory in the years 2009 and 2010. The last spectra covered a very wide wavelength interval but we reduced them and used only an interval around the Hα line as for the two previous sets of spectra. To support our periodic analysis presented in the paper, we also used two sets of UBV photometric measurements - 1) 105 observations made at the Hvar Observatory during the year 2010 and 2) 66 observations made at the Hopkins Phoenix Observatory also in 2010 (i.e. during the current eclipse).

Since we had a rich collection of the spectra covering about a half of an orbital period of ϵ Aur at our disposal, we decided to attempt to disentangle given spectra and to find some weak spectral signatures of an unseen secondary (which should again originate in a pseudophotosphere of the disk around the secondary as it was for β Lyr). We chose a long interval blueward from the Hα line containing SiII6347 and SiII6371 lines and applied a KOREL program (Hadrava 1995, 1997, 2004) to it. Since the mass ratio of ϵ Aur is still uncertain, we used a special method of solving the task (used e.g. by Harmanec et al. 2010) when we did many different solutions with various fixed values of the mass ratio in the aim to investigate whether there is any prominent "parabolic" dependence of squares of residuals χ^2 for particular "solutions" to the mass ratio. We did not find such a dependence and so we concluded that there is no measurable secondary spectrum hidden in the prominent primary spectrum (but our attempt does not exclude a possibility that the secondary itself is a close binary). Here, we note that an attempt to disentangle the ϵ Aur spectra is complicated task because spectral lines of this star are very variable and radial velocity displacements of given spectral lines are so small (due to a wide separation of the components) that the hypothetical spectrum of the secondary should be fully blended with the primary spectrum during an entire orbital cycle. Moreover, it is expected that the secondary spectrum would be in orders of a magnitude weaker than the primary spectrum. At least, we did a comparison of a "pure" primary spectrum cleared from telluric lines and permanent variations with LTE synthetic spectra and we concluded that the primary must be a low gravity object.

We realized that the Hα line undergoes prominent changes of its profile during the current eclipse. Its central intensity decreases gradually resulting in a very strong absorption which is splitted into two well separated cores close to the mid-eclipse. Moreover, its prominent emission peaks gradually disappear in a certain phase of the eclipse and reappear again after the mid-eclipse. We interpreted this behavior similarly as Kuiper et al. (1937) that it is caused by an additional absorption of a primary light in a pseudoatmosphere of the disk around a secondary. We calculated a mean out-of-eclipse Hα profile, shifted it for appropriate radial velocities (using our orbital solution presented by Chadima et al. (2010)) and subtracted it from the particular spectra observed during the eclipse. After this correction, we got rather symmetric double-absorption core profiles which evolution agree with our expectations which was an indirect proof that our interpretation and a consequent correction of the Hα profiles was correct. After that, we measured central intensities, equivalent widths and radial velocities of the corrected profiles and showed that an evolution of these quantities is consistent with our initial hypothesis about the complex Hα profiles during the eclipse. We concluded that the modeling of the Hα profiles during the eclipse could greatly help in understanding of the structure of the disk (i.e. its density and velocity distribution).

During studies of the Hα line profiles, we found out two interesting facts. The first one was that the gradual decrease of the Hα central intensity already began about three years before a predicted beginning of the eclipse. We used our previous orbital solution and showed that an angle between a sightline at that time and a sightline during a predicted mid-eclipse is about 85°, i.e. that the system was almost in elongation at that time. Therefore there is most probably also some circumbinary material responsible for this Hα line strenghtening. The second one was a revealing of a remarkable out-of-eclipse profile variation in the years 2005–2006. A blue emission wing disappeared at that period and it was replaced by a deep, blue-shifted absorption core. It was most probably caused by an additional strong absorption in a gaseous material with a negative radial velocity. This indicates a presence of either a transient outflow of a material from the primary star or of some localized circumstellar matter occulting the primary.

We applied a Fourier period analysis (using a program PERIOD written by Lenz & Breger (2005)) on central intensities and radial velocities of several silicon and iron lines during the eclipse. We discovered that their variations can reasonably be described by two periods. Moreover, the main period $66\overset{\mathrm{d}}{.}21$ was common for all analyzed sets of data. Then, we applied the period analysis also on photometric observations during a total phase of the eclipse and realized that it can also reasonably be described by two periods where the first one is indeed equal to the main period found previously which indicates that it should be real. Moreover, the same period was also reported previously by Kim (2008). However, our attempt to extrapolate the found periods to out-of-eclipse data failed. A possible interpretation of given periodic variations is that they are caused by pulsations of the primary.

4 A theoretical modeling of accretion disks

An existence of an accretion disk and eventually also other circumstellar structures in any system significantly affects observed data. There are new emission and absorption lines presented in spectra which may be blended with the lines originating in stellar atmospheres. Therefore a radial velocity curve constructed from such lines may not precisely reflect an orbital motion of given binary. Moreover, light curves (in the case of eclipsing binaries) may be greatly affected by a presence of the accretion disks and their solution can not be reasonably done without taking into account a radiation coming from the disks. Besides deriving accurate orbital solutions for such systems, a modeling of the accretion disks is also beneficial to a determination of their structure and generally, to understanding of the accretion phenomen.

First, it is necessary to make a hydrodynamic modeling of a mass transfer between stars which yields the distribution of a density and a temperature and a velocity field of the matter around the accreting star. These hydrodynamical results can then be used as input to programs which solve a radiative transfer in given circumstellar matter. It results in synthetic spectra which can be compared with the observed ones which tests whether the underlying model is realistic for a particular system. Both the hydrodynamic and radiative simulations have very high demands on computer capacities and therefore many recent programs used various physical simplifications for their models and/or they were designed to make only one- or two-dimensional calculations. However, thanks to a great increase of a computing power, there are already quite realistic programs which solves the problem in three dimensions and without critical simplifications.

There are two different ways how to construct three-dimensional models of the accretion disks. The simpler one is to compute ”analytical” models of static and axisymetric Keplerian disks using basic physical equations – a continuity equation, an angular momentum conservation equation – without time derivatives. A radial and a vertical structure of the disk are solved separately. In the angular momentum conservation equation, there is usually a viscous torque term. This term causes energy dissipation and consequently a slow accretion of the matter in the disk. A detailed description of the accretion phenomen and a modeling of a structure of the accretion disks can be find for example in a book ”Accretion Power in Astrophysics” (Frank et al. 1985). A modeling of a vertical structure for thick disks is well described by Hubený (1990). Similar modeling was already used in a connection to several real binaries with the accretion disks (see e.g. Hubený & Plavec 1991).

The second, more complicated but also more natural way is to model a mass transfer between components by a numerical solving of three-dimensional hydrodynamic equations. Such a modeling usually leads to the theoretical creation of the accretion disk and also other structures of a circumstellar matter. These models are more realistic because they are not static and axisymetric. These simulations are well described for example in a book ”Mass Transfer in Close Binary Stars” (Boyarchuk et al. 2002). The base for this modeling is the numerical solving of classical time-dependent Euler equations – a continuity equation, an angular momentum conservation equation and sometimes also an energy conservation equation. These equations are complemented by a state equation (typically an equation of an ideal gas) and a potential equation (typically a classical Roche potential). It is necessary to choose a suitable numerical scheme for given differential equations that is stable and fast-convergent. Finally, an appropriate computing domain, boundary conditions on its borders and initial conditions have to be chosen. The boundary conditions typically allow a free outflow of a matter while there is a small area of a matter inflow in a vicinity of a Lagrange point. The initial conditions typically set a homogeneous and static distribution of a very low density matter in a computational domain. This is necessary for a consistent beginning of a numerical solution and it does not affect final results. Nowadays, there are several programs designed to solve the mass transfer in three dimensions (see e.g. Boyarchuk et al. 2002; Nazarenko et al. 2005; Hayes et al. 2006).

Hydrodynamic results can then be used to calculate a synthetic spectrum coming from given circumstellar matter (a radiation from both stars should be also taken into account). To get the synthetic spectrum, it is necessary to solve the radiation transfer equation which relates the differential change in a radiation intensity and an absorbility (resp. an emissivity) of the matter which is quantified by an absorption (resp. an emission) coefficient. Usually, a simplified assumption known as *local thermodynamic equilibrium* (LTE) is used. It means that the matter is locally in thermodynamic equilibrium, although a radiation does not need to be in equilibrium. This can be satisfied in two cases – the radiation is also in equilibrium (it is fulfilled in high optical depths where the radiation can not escape) or a mutual interaction of the matter dominates over the radiation-matter interaction (it is fulfilled in dense regions with a low temperature). In the case of the local thermodynamic equilibrium, a population of allowed excitation levels of atoms is described by Boltzmann statistics which is dependent only on a temperature. The temperature is known and so it is possible to calculate the population of the various levels in the atoms which is used to compute the absorption and the emission coefficients which are finally used to solve the radiation transfer equation in given matter. But the emission coefficient contains also a scattering term which represents an amount of the radiation from other directions which is scattered to a considered direction. This term is dependent on the radiation which comes to given place from all directions which means that the problem of the radiative transfer is naturally three-dimensional since it is necessary to find a consistent solution for a whole computational domain to get the radiation escaping in a particular direction (to an observer). There are several programs which solve the radiation transfer in the LTE approximation (see e.g. Budaj & Richards 2004; Koesterke 2009).

When the conditions of the local thermodynamic equilibrium are not fulfilled, the problem of the radiative transfer needs to be solved in a full generality which is known as a *non-local thermodynamic equilibrium* (NLTE). In this case, the population of the various levels in the atoms is determined not only by collisions between the atoms but also by the radiation-matter interaction since it causes an excitation and a deexcitation of the atoms. The population of the various levels is therefore dependent on a mean intensity of the radiation in a particular place. The mean intensity is then given by a spatial integration of the intensity in a whole solid angle. Therefore the mean intensity is dependent on the particular intensities in various directions which are determined by a solution of the radiative transfer equation. The problem is thus self-consistent and it is necessary to do several iterations until the population of the various levels and the related intensities are consistent. These computations are very time consuming but there are already several programs which calculate the radiative transfer in the general NLTE case (see e.g. Juvela 1997; Carciofi & Bjorkman 2006).

Finally, it should be noted that in a full generality, it is not possible to split the problem to a separate solution of the hydrodynamics and a consequent solution of the radiative transfer since the radiation, which has its own pressure, can affect the hydrodynamic solution. But taking this fully into account would cause a very serious complication because it would be necessary to solve the radiation transfer between each two steps of the numerical hydrodynamic calculation which is almost impossible.

However, there are several programs which attempt (using some simplifications) to take an influence of the radiation to the hydrodynamics into account (see e.g. Hayes et al. 2006; González et al. 2007).

4.1 A modeling of V/R variations of Hα emission wings

Some main sequence B-type stars, called as *Be stars*, are known to have a prominent emission in the HI Balmer series and especially in the Hα line. The emission has a form of two peaks around given line where a peak with a negative (resp. a positive) radial velocity shift is denoted as a V peak (resp. an R peak). This emission lines are believed to come from disks around these stars which probably originate from equatorial mass outflows due to the critical rotation of the stars (decretion disks). On the other hand, there is also an alternative hypothesis that Be stars are in fact binaries (usually with still unresolved companions) in which the disks originate from a mass transfer (accretion disks) (Kříž & Harmanec 1975). Sometimes, reversal variations in an intensity of both peaks, called as V/R variations, have been observed for several decades. This phenomen was reported for example for ζ Tau (Ruždjak et al. 2009). An existing modeling of the V/R variations was based almost exclusively on a model of a slowly revolving elongated disk around the star, identified in physical terms with one armed oscillations in the disk (see e.g. McLaughlin 1961b,a; Okazaki 1997; Fiřt & Harmanec 2006). Therefore, we decided to conduct a simulation which could test our alternative idea that an elongated disk around the star originates from a discontinuous and short mass transfer from a companion in a binary system. This transfer may occur in eccentric binaries during a periastron passage. Moreover, such inflow of material could also be caused by density enhancement in a stellar wind in the form of coronal mass ejections from a chromospherically active star.

For our hydrodynamical simulation, we used the program ZEUS-MP, a multiprocessor clone of the original program ZEUS-3D (Hayes et al. 2006) which is designed to solve Euler equations in a three-dimensional space. We chose a hollow cylinder around the star as a computational domain. This region was filled by a very low density matter in a Keplerian rotation. This low density matter is necessary for a consistent initialization of a numerical computation but it does not affect results. A discontinuous mass transfer was simply realized by a blob of a gaseous material set into an orbit around the star. The dynamical evolution of the gas was numerically followed by solving standard hydrodynamical equations (a continuity equation and a momentum conservation equation) for an isothermal case and an inviscid gas. We chose a quadrupole potential for the star distorted by a fast rotation. The quadrupole potential is expected to cause a slow revolution of the formed disk around the star as was already demonstrated for example by Fiřt & Harmanec (2006).

This first simulation has several simplifications (which we intend to improve with further simulations) but we do not think that they seriously affect the results on a qualitative basis. The main simplification is the assumption of an inviscid isothermal gas. The viscosity of the orbiting gas is expected to destroy any asymmetry in the disk and all observed effects should be only temporal. A gravitation of the orbiting companion, which is expected to speed up a disk revolution, is also still not included. The simplifications also involve the way how the discontinuous mass transfer was represented. On the other hand, we emphasize that we make no assumptions about the disk in our model but we gradually mathematically construct it via a non-linear hydrodynamic modeling of the evolution of a discontinuous mass inflow.

Our simulation led to the formation of an elongated accretion disk around the star with a denser region near its apocetrum which underwent a slow prograde rotation with a period of about 16 years. The prograde rotation is caused by the quadrupole term of the gravitational potential. This result is in qualitative agreement with several papers which studied the influence of the quadrupole term of the gravitational potential of fast-rotating stars on a precession rate of the disks around them (see e.g. Savonije & Heemskerk 1993; Okazaki 1996; Fiřt & Harmanec 2006).

To model the emission profiles of the Hα line originating in the disk, we used the program SHELLSPEC written by Budaj & Richards (2004). It solves the radiative transfer along the line of sight in an optically thin environment assuming LTE. The modeling led to double-peaked emission line profiles. The denser region in the disk emits more radiation and its revolution around the star combined with a rotation of the disk particles resulted in the V/R variations, similar to those observed for several Be stars.

5 Conclusion

This thesis is based on four papers relating to binaries with (accretion) disks. A summary of all original results obtained from our analyses follows:

- An analysis of the interacting eclipsing binary β Lyr was based on 703 spectra mostly in the Hα wavelength region which were complemented by 255 photometric UBV observations. A new quadratic ephemeris was calculated for β Lyr which updated the previous one published by Harmanec & Scholz (1993). Several limited spectral regions were chosen and a spectral disentangling was applied to them. This led to the first detection of a weak secondary spectrum which most probably originates in a pseudophotosphere of a thick accretion disk around the hidden secondary. Central intensities and equivalent widths of several prominent absorption lines of the primary were measured and corrected for a light curve of the system. A prominent increase of their strength during a primary eclipse was revealed after the correction which was interpreted as an indirect detection of a new satellite spectrum caused by an additional absorption of a primary light going through circumstellar structures around the secondary. Central intensities of V and R peaks of the Hα line were measured and again corrected for the light curve. A pronounced orbital variation of both peaks almost disappeared after this correction which was a strong indication that they indeed originate outside of an orbital plane, most probably in jet-like structures.

- A total amount of 1265 radial velocities since the year 1899 and 908 photometric observations since the year 1848 from various sources was accumulated and used to compute a new ephemeris and an orbital solution for ϵ Aur. Two independent programs (PHOEBE and FOTEL) were used for the solution and an iterative process was applied which consisted of a determination of a period and an epoch of a primary minimum by solving a light curve while the rest of orbital parameters was derived by solving a radial velocity curve. Our solution was then compared with the previous solution by Wright (1970) and the current independent solution by Stefanik et al. (2010). Finally, two generally accepted facts about ϵ Aur were disputed – a reality of a central brightening and a reality of a variability of a width and a duration of primary eclipses.

- An analysis of the long-period eclipsing binary ϵ Aur was based on 353 spectra in the Hα wavelength region which were complemented by 171 photometric UBV observations. An unsuccessful attempt to disentangle give spectra was made which led to the conclusion that there is no measurable secondary spectrum hidden in the prominent primary spectrum. A comparison of the mean primary spectrum with LTE synthetic spectra revealed that the primary must be a low gravity object. A complex behaviour of the Hα profile during the current eclipse was studied and interpreted as a consequence of the additional absorption of a primary light in the pseudoatmosphere of the disk around the secondary. A correction for a mean out-of-eclipse Hα profile was applied for all spectra during the eclipse which led to rather symmetric double-absorption profiles whose evolution and measured characteristics agreed with our expectations which was a proof that our initial hypothesis was correct. It was realized that an increase in a strength of the Hα absorption already began when the system was almost in an elongation which indicated that there should be some circumbinary material in the system. A remarkable out-of-eclipse Hα profile variation in the years 2005–2006 was reported. A period analysis made on photometric data and various quantities of spectral lines revealed that the data can be reasonably described by two periods while the main period $66\overset{\mathrm{d}}{.}21$ is common for all analyzed quantities, therefore it should be real.

- An initial simulation that could prove an alternative idea that elongated disks around Be stars originate from discontinuous and short mass transfers from companions in binary systems was made. A three-dimensional hydrodynamic program ZEUS was used to simulate an evolution of a blob of a mass set into an orbit around the star distorted by a fast rotation. The hydrodynamic simulation led to a formation of an elongated accretion disk around the star with a denser region near its apocentrum which underwent a slow prograde rotation with a period of about 16 years. The prograde rotation of the disk was caused by a quadrupole term of a gravitational potential. A program SHELLSPEC was used to model emission profiles of the Hα line originating in the disk which led to double-peaked emission line profiles with V/R variations similar to those observed for several Be stars.

References

Abt, H. A. 1983, Annual review of Astronomy&Astrophysics, 21, 343

Ak, H., Chadima, P., Harmanec, P., et al. 2007, Astronomy&Astrophysics, 463, 233

Argelander, F. W. A. 1859, De stella Beta Lyrae variabili commentatio altera

Backman, D. E., Becklin, E. E., Cruikshank, D. P., et al. 1984, Astrophysical Journal, 284, 799

Balachandran, S., Lambert, D. L., Tomkin, J., & Parthasarathy, M. 1986, Monthly Notices of the Royal Astronomical Society, 219, 479

Belopolsky, A. 1897, Astrophysical Journal, 6, 328

Bennett, P. D., Ake, T. B., & Harper, G. M. 2005, in Bulletin of the American Astronomical Society, Vol. 37, American Astronomical Society Meeting Abstracts #206, 495

Bisikalo, D. V., Harmanec, P., Boyarchuk, A. A., Kuznetsov, O. A., & Hadrava, P. 2000, Astronomy&Astrophysics, 353, 1009

Boyarchuk, A. A., Bisikalo, D. V., Kuznetsov, O. A., & Chechetkin, V. M. 2002, Mass transfer in close binary stars, ed. Boyarchuk, A. A., Bisikalo, D. V., Kuznetsov, O. A., & Chechetkin, V. M.

Budaj, J. & Richards, M. T. 2004, Contributions of the Astronomical Observatory Skalnate Pleso, 34, 167

Cameron, A. G. W. 1971, Nature, 229, 178

Carciofi, A. C. & Bjorkman, J. E. 2006, Astrophysical Journal, 639, 1081

Carroll, S. M., Guinan, E. F., McCook, G. P., & Donahue, R. A. 1991, Astrophysical Journal, 367, 278

Chadima, P., Fiřt, R., Harmanec, P., et al. 2011a, Astronomical Journal (in press), ArXiv e-prints – 1104.2725

Chadima, P., Harmanec, P., Bennett, P. D., et al. 2011b, Astronomy&Astrophysics (in press), ArXiv e-prints – 1105.0107

Chadima, P., Harmanec, P., Yang, S., et al. 2010, Information Bulletin on Variable Stars, 5937, 1

Curtis, R. H. 1911, Publ.Allegheny Obs. 2, 73

De Greve, J. P. & Linnell, A. P. 1994, Astronomy&Astrophysics, 291, 786

Eggleton, P. P. & Pringle, J. E. 1985, Astrophysical Journal, 288, 275

Ferluga, S. 1990, Astronomy&Astrophysics, 238, 270

Fiřt, R. & Harmanec, P. 2006, Astronomy&Astrophysics, 447, 277

Frank, J., King, A. R., & Raine, D. J. 1985, Accretion power in astrophysics, ed. Frank, J., King, A. R., & Raine, D. J.

Gaposchkin, S. 1956, Zeitschrift für Astrophysik, 39, 133

González, M., Audit, E., & Huynh, P. 2007, Astronomy&Astrophysics, 464, 429

Goodricke, J. & Englefield, H. C. 1785, Royal Society of London Philosophical Transactions Series I, 75, 153

Guinan, E. F. & Dewarf, L. E. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 279, Exotic Stars as Challenges to Evolution, ed. C. A. Tout & W. van Hamme, 121

Hadrava, P. 1990, Contributions of the Astronomical Observatory Skalnaté Pleso, 20, 23

Hadrava, P. 1995, Astronomy&Astrophysics Supplement, 114, 393

Hadrava, P. 1997, Astronomy&Astrophysics Supplement, 122, 581

Hadrava, P. 2004, Publ. Astron. Inst. Acad. Sci. Czech Rep., 92, 15

Harmanec, P. 1970, Astrophysics and Space Science, 6, 497

Harmanec, P. 1992, Astronomy&Astrophysics, 266, 307

Harmanec, P. 2002, Astronomische Nachrichten, 323, 87

Harmanec, P., Aerts, C., Prša, A., Verhoelst, T., & Kolenberg, K. 2010, Astronomy&Astrophysics, 520, A73

Harmanec, P., Morand, F., Bonneau, D., et al. 1996, Astronomy&Astrophysics, 312, 879

Harmanec, P. & Scholz, G. 1993, Astronomy&Astrophysics, 279, 131

Hayes, J. C., Norman, M. L., Fiedler, R. A., et al. 2006, Astrophysical Journal Supplement Series, 165, 188

Herbig, G. H. & Boyarchuk, A. A. 1968, Astrophysical Journal, 153, 397

Hilditch, R. W. 2001, An Introduction to Close Binary Stars, ed. Hilditch, R. W.

Hoard, D. W., Howell, S. B., & Stencel, R. E. 2010, Astrophysical Journal, 714, 549

Huang, S. 1963, Astrophysical Journal, 138, 342

Huang, S. 1965, Astrophysical Journal, 141, 976

Hubený, I. 1990, Astrophysical Journal, 351, 632

Hubený, I. & Plavec, M. J. 1991, Astronomical Journal, 102, 1156

Ilijic, S., Hensberge, H., Pavlovski, K., & Freyhammer, L. M. 2004, in Astronomical Society of the Pacific Conference Series, Vol. 318, Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, ed. R. W. Hilditch, H. Hensberge, & K. Pavlovski, 111

Juvela, M. 1997, Astronomy&Astrophysics, 322, 943

Kaluzny, J., Stanek, K. Z., Krockenberger, M., et al. 1998, Astronomical Journal, 115, 1016

Kim, H. 2008, Journal of Astronomy and Space Sciences, 25, 1

Kippenhahn, R. & Weigert, A. 1967, Zeitschrift für Astrophysik, 65, 251

Kloppenborg, B., Stencel, R., Monnier, J. D., et al. 2010, Nature, 464, 870

Koesterke, L. 2009, in American Institute of Physics Conference Series, Vol. 1171, American Institute of Physics Conference Series, ed. I. Hubený, J. M. Stone, K. MacGregor, & K. Werner, 73

Kopal, Z. 1971, Astrophysics and Space Science, 10, 332

Kuiper, G. P. 1941, Astrophysical Journal, 93, 133

Kuiper, G. P., Struve, O., & Strömgren, B. 1937, Astrophysical Journal, 86, 570

Křížž, S. & Harmanec, P. 1975, Bulletin of the Astronomical Institutes of Czechoslovakia, 26, 65

Lenz, P. & Breger, M. 2005, Communications in Asteroseismology, 146, 53

Linnell, A. P. 2000, Monthly Notices of the Royal Astronomical Society, 319, 255

Linnell, A. P. 2002, Monthly Notices of the Royal Astronomical Society, 332, 21

Linnell, A. P. & Hubený, I. 1996, Astrophysical Journal, 471, 958

Lissauer, J. J. & Backman, D. E. 1984, Astrophysical Journal Letters, 286, L39

Ludendorff, H. 1903, Astronomische Nachrichten, 164, 81

Ludendorff, H. 1912, Astronomische Nachrichten, 192, 389

McLaughlin, D. B. 1961a, Journal of the Royal Astronomical Society of Canada, 55, 73

McLaughlin, D. B. 1961b, Journal of the Royal Astronomical Society of Canada, 55, 13

Morris, S. C. 1962, Journal of the Royal Astronomical Society of Canada, 56, 210

Nazarenko, V. V. & Glazunova, L. V. 2006, Astronomy Reports, 50, 380

Nazarenko, V. V., Glazunova, L. V., & Shakun, L. S. 2005, Astronomy Reports, 49, 284

Okazaki, A. T. 1996, Publications of the Astronomical Society of Japan, 48, 305

Okazaki, A. T. 1997, Astronomy&Astrophysics, 318, 548

Paczyński, B. 1971, Annual Review of Astronomy and Astrophysics, 9, 183

Perryman, M. A. C. & ESA. 1997, The HIPPARCOS and TYCHO catalogues, ESA SP Series 1200 (Noordwijk, Netherlands: ESA Publications Division)

Prša, A. & Zwitter, T. 2005, Astrophysical Journal, 628, 426

Raghavan, D., McAlister, H. A., Torres, G., et al. 2009, Astrophysical Journal, 690, 394

Ruždjak, D., Božić, H., Harmanec, P., et al. 2009, Astronomy&Astrophysics, 506, 1319

Sadakane, K., Kambe, E., Sato, B., Honda, S., & Hashimoto, O. 2010, Publications of the Astronomical Society of Japan, 62, 1381

Sahade, J. 1980, Space Science Reviews, 26, 349

Saito, M. & Kitamura, M. 1986, Astrophysics and Space Science, 122, 387

Savonije, G. J. & Heemskerk, M. H. M. 1993, Astromony&Astrophysics, 276, 409

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, Astronomy&Astrophysics Supplement Series, 96, 269

Schmitt, H. R., Pauls, T. A., Tycner, C., et al. 2009, Astrophysical Journal, 691, 984

Secchi, A. 1867, Sugli spettri prismatici delle stelle fisse, Memorie diMatematica e di Fisica Societa Italiana delle Scienze, 3 Ser., Vol. 1, Part I., p. 67

Simon, K. P. & Sturm, E. 1994, Astronomy&Astrophysics, 281, 286

Skulsky, M. Y. 1975, Astronomicheskii Zhurnal, 52, 710

Skulsky, M. Y. & Topilskaya, G. P. 1991, Pis'ma Astronomicheskii Zhurnal, 17, 619

Smith, B. A. & Terrile, R. J. 1984, Science, 226, 1421

Stefanik, R. P., Torres, G., Lovegrove, J., et al. 2010, Astronomical Journal, 139, 1254

Stencel, R. 1985, The Recent Eclipse of Epsilon Aurigae, NASA Conf. Publ. 2384

Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, Astronomical Journal, 97, 1451

Struve, O. 1956, Publications of the Astronomical Society of the Pacific, 68, 27

van Leeuwen, F. 2007, in Astrophysics and Space Science Library, ed. F. van Leeuwen, Vol. 350 (Berlin: Springer)

Wilson, R. E. 1974, Astrophysical Journal, 189, 319

Wilson, R. E. & Devinney, E. J. 1971, Astrophysical Journal, 166, 605

Wolk, S. J., Pillitteri, I., Guinan, E., & Stencel, R. 2010, Astronomical Journal, 140, 595

Wright, K. O. 1970, Vistas in Astronomy, 12, 147

Zhao, M., Gies, D., Monnier, J. D., et al. 2008, Astrophysical Journal Letters, 684, L95