AN 323 (2002) 2, 87–98

The ever challenging emission-line binary β Lyræ

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Received *April 29, 2002*; accepted *2002 March 14*

Abstract. A brief history of investigations of β Lyr, an emission-line binary and one of the first ever discovered Be stars is presented. A rather fast progress in the understanding of this enigmatic object during the past fifteen years is then discussed in some detail. The current picture of β Lyr is that it is an eclipsing binary in a stage of mass transfer between the components. The mass-losing star is a B6-8II object, with a mass of about 3 $M_\odot$, which is filling the Roche lobe and sending material towards its more massive companion at a rate of about 2×10^{-5} $M_\odot$ yr^{-1}. This leads to the observed rapid increase of the orbital period at a rate of 19 s per year. The mass-gaining star is as early B star with a mass of about 13 $M_\odot$. It is completely hidden inside an opaque accretion disk, jet-like structures, perpendicular to the orbital plane and a light-scattering halo above the poles of the star. The observed radiation of the disk corresponds to an effective temperature which is much lower than what would correspond to an early B star. The disk shields the radiation of the central star in the directions along the orbital plane and redistributes it in the directions perpendicular to it. That is why the mass-losing star appears brighter of the two in the optical region of the spectrum. At present, rather reliable estimates of all basic properties of the binary and its components are available. However, in spite of great progress in understanding the system in recent years, some disagreement between the existing models and observed phase variations still remains, both for continuum and line spectrum, which deserves further effort.

Key words: hot emission-line (OBAe) stars – binaries – spectral and light changes – models of light curve and disk structure

1. An early development of the ideas about β Lyr

β Lyræ (10 Lyr, HD 174638, HR 7106) is the second brightest star in the beautiful constellation of Lyra, observable on the northern hemisphere. The star was known for many centuries to various civilizations and got different names from them: *Tien-Tchaj* from ancient Chinese observers and *Sheliak* from Arabs (which probably comes from the Persian word shalyak: turtle). In September 10, 1784, John Goodricke, a deaf-mute grandson of Sir John Goodricke, recorded the first light decrease of β Lyr which he later found to be periodic with a period of slightly less than 13 days (Goodricke 1785). β Lyr thus became the second ever discovered eclipsing binary (after Algol, discovered also by Goodricke 1783 in the years 1782-83 and independently also by a German amateur astronomer Johann G. Palitsch). Goodricke, who was eighteen years old at the time of his discovery of Algol light changes, correctly interpreted the periodic light decreases as eclipses of the visible star by a dark companion (mentioning a rotating star with spots as an alternative) and it is probable that he believed in a similar interpretation also for β Lyr. It is also interesting to mention Goodricke's (1785) remark that already W. Herschel had suspected that either β Lyr or γ Lyr must be variable.

Goodricke himself was unable to continue his observations since he died young on April 20, 1786. However, the light variations of β Lyr were intensively studied by other visual observers like Westphal and especially Argelander who collected also the data from other observers (see, e.g. Argelander 1844, 1857, 1859, 1869, 1898). Already Argelander (1859) noted that the period of light variations of β Lyr was growing steadily since the time of the first Goodricke's observations.

The binary interpretation had remained putative until spectroscopic observations became available. When Secchi (1867) published his 1866 observations of stellar spectra secured with a visual spectroscope, he reported the discovery of the Hβ emission in the spectrum of β Lyr, seen in addition to normal absorption-line spectrum found for other stars. β Lyr thus became the very first Be star known. Already the early observers using the first photographic spectra (without any wavelength or flux calibration), Lockyer (1894) and Maury (1897), noted the presence of two sets of absorption lines. The first one, called the B8 spectrum, was clearly changing its position while the other one, called the B5 spectrum, was fixed in position.

In 1891, Fleming (1891) reported her investigation of the prismatic photographic spectra of β Lyr from Harvard Observatory. She discovered periodic oscillations of the position of the emission lines with respect to the absorption lines observed. Her finding was also reported by Pickering (1891). Altogether 307 early Harvard spectrograms (the first one from December 1886) were later carefully re-investigated by Maury (1933) who derived a relative radial-velocity (RV hereafter) curve from them.

In 1892, Bélopolsky in Pulkowa obtained the very first series of *wavelength-calibrated* spectra of β Lyr and derived the first RV curves. A few years later he improved the spectrograph and obtained another, more accurate RV curve (cf. Bélopolsky 1893a, 1893b, 1894, 1897a, 1897b). He found that the RV curve of the Hβ emission varied in antiphase to the RV curve defined by the absorption lines and concluded that the emission line comes from the other, more massive component of the binary. His observations imply the masses of 8.4 and 17.6 $M_\odot$ for the absorption and emission-line star, respectively.

Another early paper worth of mentioning is that by Myers (1898). Myers mentions three possible causes of periodic light changes: rotating star with an uneven distribution of surface brightness, a rather complicated hypothesis of colliding meteoric swarms, and the eclipsing-binary model which he then discusses in some detail, applying already the idea of equipotential surfaces to β Lyr.

Curtiss (1911) obtained a new series of spectrograms of β Lyr and discussed a possibility that the emission lines originate mostly from a gaseous envelope around the whole system. Many attempts to find the lines of the other component followed which resulted in the finding that the spectrum is extremely complex, complicated and variable. The history of investigation of β Lyr is skilfully summarized in a review by Sahade (1980) and I am not going to repeat it here. I shall restrict myself to only a few details interesting from the historical perspective.

The man who devoted a lot of energy to understand the secrets of β Lyr was Otto Struve, supported and followed by his students, especially by S.-S. Huang and J. Sahade. He succeeded to accumulate lots of precious data on β Lyr and to contribute to the identification of several distinct sets of spectral lines. In his Henry Norris Russell Lecture, given at the Urbana, Illinois meeting of the American Astronomical Society on August 19, 1957, Struve (1958) estimated that already to that date, β Lyr had been studied in more than 200 publications and by several hundreds of astronomers and that millions of dollars had been expended during the past century and a half toward the solution of the riddle of β Lyr.

In the retrospect, one can note, how the strong belief in some physical principles and at that time available models led in fact to the dead ends for some time. Astronomers in thirties of the twentieth century believed in the universal validity of the mass-luminosity relation. Besides – specifically for β Lyr – the solution of the observed light curve, based on the assumption of mutual eclipses of two ellipsoidal stars, led to the conclusion that the invisible object is an A or F star, smaller than the B8II star (Myers 1898, Danjon 1928, Kopal 1941 and several others). Since the large amplitude of the RV curve of the absorption-line star resulted in a very large mass function, the consequence was that β Lyr was considered to be one of the most massive binaries known. For instance Kuiper (1941) in his important study adopted masses of 78 and 52 $M_\odot$ for the visible and 'invisible' star, respectively. It is interesting to note that Kopal (1941) had already expressed some doubts about the strict validity of the mass-luminosity relation. He was also aware of the problem of the missing source of radiation to excite the B5 spectrum. Besides, he estimated that the mass loss via stellar wind cannot explain the large secular increase of the orbital period. Yet, he also advocated a model of two very massive stars, with a total mass exceeding 95 $M_\odot$.

At the same time, the evidence of the circumstellar matter inside and around the system and some indications of the presence of a disk around the 'invisible' star were in fact already available. It is interesting to mention in this connection that Baxandall and Stratton (1930) – who re-analyzed early Curtiss' spectrograms along with Cambridge spectra – were the first to note additional absorption lines, redshifted for some 200 km s^{-1}, which appeared in the spectrum of β Lyr just before the primary mid-eclipse. Shortly thereafter, these satellite lines were also reported by Maury (1933). While outlining the tentative model of the binary, Baxandall and Stratton write: "There are two ellipsoidal stars of spectral types B8 and B5. The B8 star is the larger but less massive star, with a brighter surface. The B5 star is, however, surrounded by a gaseous envelope which is larger than the B8 star, fairly transparent to the radiation from both stars (save for the lines that the envelope emits) and radiating a broad bright line spectrum of hydrogen and helium. Circulating currents in the outer envelope, not constant in their relation to the orbital motion of the bodies, account for irregularities both in the light curve and in the spectra. One such current perhaps in the nature of an equatorial acceleration is manifested by a set of strong lines displaced to the red just before principal minimum." In my view, this is an early anticipation of the (accretion) disk in β Lyr.

Struve (1941) carried out the first really quantitative study of these satellite absorptions and distinguished two sets of them: red-shifted absorptions before, and blue-shifted absorptions after the centre of the primary eclipse. He interpreted these lines as originating in two streams of gas, flowing from one star to the other and vice versa. He suggested that the basically stationary 'B5' spectrum originates in an expanding circumbinary envelope which has the form of an extended disk in the orbital plane of the binary.

Kuiper (1941) was the first to consider the possibility of the mass transfer from the visible to the 'invisible' star. He analyzed the dynamics of the gas streams on the basis of the Roche model and also considered the consequences of the mass transfer for the changes of the orbital period. However, since he was convinced that the visible star is the more massive one of the two, he was unable to explain the observed *increase* of the orbital period. He also interpreted the 'B5' spectrum as originating in a circumbinary gaseous structure which, in his model, had a form of an outflowing spiral starting from the Lagrangian point L_2.

In his short note on the cyclic variation in the shape of the observed light curve, Guthnick (1945) was arguing that there is an alternating exchange of mass between the two stars in a cycle of several, possibly 18 years. (A remarkable thing on this note is also the fact that it was communicated by Guthnick from Potsdam to the Bureau of Astronomical telegrams in Denmank at the dawn of World War II where it was published just one month before the actual end of the war.)

It appears that Gaposchkin (1956) should be credited for being the first who explicitly pointed out that the 'invisible' star is actually hidden in dense structures of circumstellar matter and is indeed the more massive of the two, as Bélopolsky correctly concluded. It is clear, however, that new observational data and interactions among Struve, Sahade, Huang and Gaposchkin led gradually all of them to the realization that the B8 component could be the less massive star of the two - compare, for instance, papers by Struve (1957a, 1957b, 1958), Sahade (1958) and Huang (1962). In the majority of more recent papers, the breakthrough in the understanding of the apparent underluminosity of 'invisible' component is usually associated with Huang's (1963) paper in which he explicitly introduced the concent of the large-scale mass transfer between the binary components of β Lyr and especially the concept of an accretion disk in which *the more massive* 'invisible' star is hidden. He also pointed out that the velocities of the satellite lines correspond to roughly Keplerian velocities of the gas stream which flows from the B8 component and encircles the 'invisible' star. Huang explained that an important role of an opaque disk is to cause a longer duration of the eclipses than what would correspond to eclipses of two stars only. Note also that he pictured the disk as a geometrically thin disk.[1]

Adopting Huang's ideas, Wilson (1974) presented the very first quantitative model of the light curve of a binary with one component hidden inside a disk. He demonstrated that the observed light curve of β Lyr cannot be modelled either by eclipses of two stars without a disk or by a model with a thin disk only. Clearly distinguishing between the relative luminosities and relative observed fluxes of both bodies, he was able to explain the apparent underluminosity of the star hidden in the disk. Modelling the light curve, he estimated the most probable mass ratio to be either 4.2 or 6.0 and the rate of mass transfer of 3×10^{-5} $M_\odot yr^{-1}$. He also derived approximate dimensions of the disk and showed that the central star must be completely hidden within it, otherwise one would observe a narrow stellar eclipse near the centre of the broad secondary eclipse.

Huang's explanation of satellite lines was elaborated further by Batten and Sahade (1973) who pointed out that the natural explanation for both sets of them, investigated by Struve (1941), is that they originate from those parts of the gaseous disk around the invisible star which are seen projected against the visible star in proper phases of the eclipse.

2. The picture of β Lyr in the epoch of about 1985-1990

It may be useful to summarize briefly what principal observational facts were accumulated by the time when Plavec (1985) updated Sahade's (1980) review and how β Lyr was understood and interpreted at that era.

2.1. Observational facts

2.1.1. The continuous spectrum

The light curve of β Lyr is secularly rather stable and has two eclipses separated precisely by $0\overset{\mathrm{P}}{.}5$, indicative of a circular orbit. In the optical region, the object becomes for about $1\overset{\mathrm{m}}{.}0$ fainter in the primary mid-eclipse than it is at elongations. The primary eclipse is the eclipse of the 'visible' component by the 'invisible' and more massive one. During the secondary eclipse, the light decrease with respect to elongations amounts to about $0\overset{\mathrm{m}}{.}5$. (The eclipses can easily be monitored by a naked eye since at maximum β Lyr is very nearly as bright as γ Lyr.) In the satellite UV region, both eclipses become shallower with decreasing wavelength and below 1600 Å the secondary eclipse becomes deeper that the primary one. The same is also true for the IR light curves obtained and analyzed by Jameson & Longmore (1976) at five passbands with effective wavelengths from 1200 nm to 8600 nm, and by Zeilik et al. (1982) who obtained IR light curves at J, H, K, L, and M passbands (1200 nm to 4600 nm). While the 1200 nm light curve has a deeper primary minimum in accordance with the optical light curves, both minima become comparable at 3600 nm and the 8600 nm curve has the secondary minimum substantially deeper than the primary one. This curve also has *unequal maxima* at elongations, the brightness of the system being lower at the elongation when the B6-8II component is receding than in the other one. The terms *primary component* and *secondary component* are alternatively used in the astronomical literature to denote either the stars eclipsed in the primary and secondary minima, or the more massive and less massive star, respectively. For that reason, and considering what was just said about the character of the light curves, I prefer to avoid the use of these terms in connection with β Lyr. In the rest of this paper, I shall instead use the terms *star 1* for the more massive 'invisible' star, and *star 2* for the B8 star with a well-defined RV curve.

Observations of the true energy distribution of the components of β Lyr are complicated by the presence of numerous emission lines, especially in the UV regions. Plavec (1987) who investigated the energy distribution at various orbital phases concluded that both components have peculiar continuous spectra. In the optical and near IR regions, the slope of the energy distribution of *star 1* resembles a model spectrum with about 8500 K while that of *star 2* corresponds roughly to 13000 K but the Balmer jump would require something like 16000 to 17000 K and discrepancies are also notable in the red and near-IR parts of the spectrum.

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[1] As pointed out to me by the referee, a likely link between β Lyr and ε Aur is of a special historical interest. Although the two binaries differ enormously in their orbital periods and probably also in their evolutionary stage, their geometries are topologically similar. Indeed, Huang (1965) used very similar geometrical considerations in his disk model of ε Aur as for β Lyr. Although his model has been superseded by the work of Wilson (1971) and Carroll et al. (1991), the development of the conceptual connection between both accretion-disk binary models still makes a fascinating reading.

2.1.2. The line spectrum

Sorting out the wealth of spectral data, one can distinguish at least six systems of IR, optical and UV lines:

1. **The B6-8II spectrum:** Strong and relatively sharp (v sin i= 45 – 65 km s^{-1}) absorption lines of *star 2*, visible at all orbital phases, which define its RV curve with a full amplitude of 370 km s^{-1}.
2. **The B-type "shell" absorption spectrum:** The main absorption components of He I lines, Balmer lines and many metallic lines define an absorption spectrum which was originally classified as the 'B5 spectrum' and was believed to belong to *star 1*. All lines of this spectrum are blue-shifted by various amounts, up to 200 km s^{-1} (this shift varies from line to line and obviously also secularly with time) and stronger lines have several components with different RVs. Numerous absorption lines observed in the satellite UV spectra of β Lyr show very similar patterns of behavior as described above for the optical shell lines. This is also true for the strong resonance lines of ions like C IV or Si IV.
3. **The emission spectrum:** Strong emission lines of H I, He I and of metallic lines (which are especially pronounced in the UV regions), vary in intensity both with the orbital phase and secularly. The RV measured on the wings of these lines follows a sinusoidal RV curve with an amplitude of about 30 km s^{-1} which does not coincide with the orbital motion of either binary component and attains its maximum at orbital phase $0\overset{\mathrm{P}}{.}30$.
4. **The satellite spectrum:** Strong additional absorption lines are observed only in narrow phase intervals before and after the primary mid-eclipse (of *star 2* by *star 1* and its disk). They are red-shifted before, and blue-shifted after the mid-eclipse, in both cases by about 200 km s^{-1}.
5. **Secondary Si II 2 absorption spectrum:** First noted by Sahade (1966), this pair of weak absorption lines was studied by Skulskij (1975) who found that their RV varies in an exact anti-phase to the RV curve of *star 2*.
6. **The 'interstellar' lines:** Sharp and quite strong lines of Ca II or Si II in the optical spectrum, and of additional ions in the UV, are observed with a RV of some -17 km s^{-1}. This value is identical to the systemic velocity of β Lyr. There exists, therefore, a definite possibility that these lines are predominantly circumstellar.

2.2. Interpretation

A rather generally adopted picture of β Lyr, summarized, for instance, by Tomkin and Lambert (1987), was the following: β Lyr is a system undergoing a large-scale mass exchange, with mass flowing from *star 2* towards *star 1*. The process is already in such a stage that the initially more massive *star 2* has already transferred most of its mass towards *star 1* and became the less massive of the two. While everybody agreed that *star 1* is indeed the more massive one, no accurate enough component masses were known and their estimates were only based on indirect methods. Mass ratios M_1/M_2 between about 3 and 7 were considered. Most investigators adopted Woolf's (1965) determination:

M_1 = 11.6 M$_\odot$ and M_2 = 2.05 M$_\odot$.

Evidence in favour of large-scale mass exchange in β Lyr was gradually also accumulated via abundance analyses of the spectra of *star 2* through the works of Boyarchuk (1959), Leushin et al. (1979), Balachandran et al. (1986) and Dimitrov (1987) who demonstrated that carbon is underabundant, and nitrogen and oxygen are overabundant in the atmosphere of *star 2*, precisely as predicted by the theory of mass transfer.

3. Progress in understanding β Lyr during the last two decades

Introduction of new observing techniques, namely spectroscopy with electronic detectors, spectro-interferometry, spectro-polarimetry and radio telescopes of a new generation as well as great progress in theoretical modelling led also to new attempts to unravel the mysteries of β Lyr.

A few new attempts to improve the knowledge of the basic physical elements appeared. Dobias and Plavec (1985) analyzed their Lick observations and continuum-energy scans of the brightest visual component to β Lyr, β Lyr B = HD 174664, which is gravitationally bound to β Lyr. Comparing the scans to Kurucz's model atmospheres, they estimated the effective temperature and gravity of this star and concluded that it is a B6V star. With the help of this determination, they estimated the distance to β Lyr to be between 345 and 400 pc, adopting 370 ps as the most probable value. They then derived absolute visual magnitudes of the two bodies in β Lyr with the help of this distance and Wilson's (1974) light-curve solution to be $-4\overset{\mathrm{m}}{.}1$ and $-3\overset{\mathrm{m}}{.}3$, with $E(B-V)$ = $0\overset{\mathrm{m}}{.}04$. They therefore concluded that *star 2* is a B8.5-9II-Ib object. They pointed out that – taken at face value – the age of β Lyr B based on the comparison of the derived properties with the evolutionary models should be 48 millions of years, while β Lyr as a product of large-scale mass exchange should not be older than 20-30 millions of years according to model calculations by Ziolkowski (1965) who adopted Woolf's (1965) masses.

Herczeg (1987) made an interesting attempt to investigate the question first raised by Goodricke (1785), namely why Cassini did not note the variability of β Lyr while using it and γ Lyr as two of the comparion stars in his visual observations of Nova Vul 1670 = GK Vul. Herczeg took advantage of the fact that the light curve of GK Vul was reconstructed from Cassini's and Hevelius' observations by Shara et al. (1985). Herczeg concluded that none of the available ephemerides would allow a truly reliable extrapolation of the times of β Lyr minima back to 1671 and admitted that there was a modest chance that the observers had missed the variable near its deep primary minimum.

Balachandran et al. (1986) obtained and analyzed a series of Reticon spectra of β Lyr. Their main goal was to derive the chemical composition of the atmosphere of *star 2*, as already mentioned. They found the best-fit effective temperature of 13300 K which corresponds to spectral type B6II rather then to B8II. They also improved the value of the projected velocity of rotation of *star 2* to 65 ±6 km s^{-1}.

Harmanec (1990) used their new values and the assumption that *star 2* fills the corresponding Roche lobe and that its rotation and the binary revolution are synchronized to a new estimate of probable component masses. He arrived at the masses between 13.0 and 15.3 $M_\odot$, and between 3.2 and 5.4 $M_\odot$ for *star 1* and *star 2*, respectively. (For $v \sin i$ derived earlier from photographic spectra it would be 11 and 1.5 $M_\odot$.)

Two very important studies appeared a year later. Skulskij and Topilskaya (1991), using high-dispersion CCD spectra, confirmed an earlier report by Skulskij (1975) that the RV of Si II 2 doublet defines a RV curve in anti-phase to that of *star 2* and conluded that the lines originate in the atmosphere of *star 1*, an A5III star according to them. They derived the mass ratio of 4.28 ±0.13. (Shortly thereafter, Skulskij 1992 published another study based on a larger number of CCD spectrograms where he improved the value of the mass ratio to 4.6 ±0.1.)

Hubeny and Plavec (1991) attempted to set stringent constraints on the properties of β Lyr using geometrical arguments, observed continuum energy distribution and especially the new theoretical models of the accretion disk for which the vertical structure was self-consistently calculated with a computer program. They concluded that most of the observed optical radiation from *star 1* comes from the disk rim and suggested that the UV radiation comes from a small unocculted part of the polar regions of *star 1*.[2] To explain the observed radiation they needed to assume that the current mass transfer rate is close to 10^{-4} $M_\odot$ per year. They supported the idea that *star 1* is a normal main-sequence object of a spectral class near B0.5V. Their best-fit solution led to radii of 5.5 and 12 $R_\odot$ for *star 1* and *star 2*, respectively, the height of the disk rim being 6 $R_\odot$ and the orbital inclination $i = 83^\circ$. While these values certainly represent a large step forward to understanding the properties of the system, one should be aware that the accurate numerical values should not be taken too literary. Hubeny and Plavec (1991) adopted Woolf's (1965) masses for the binary throughout their study, which define the separation of the components as well as the radius of *star 2*.

Hubeny and Plavec's model of a low-mass disk was challenged by Wilson and Terrell (1992) who argued that the disk in β Lyr had to be a massive one, something like 0.5 $M_\odot$. In doing so, they referred to earlier studies of Wilson (1981, 1982) who developed structural models of self-gravitating disks assuming that the gravitational potential can be approximated by two point masses for the binary components and by a thin wire for the disk. In particular, Wilson & Terrell claimed that the non-self gravitating disk assumed by Hubeny and Plavec would require a large pressure gradient in its outer parts to avoid a radial collapse. Their criticism was answered by Hubeny et al. (1994) who showed that the structure of the low-mass disk is derived self-consistently and that the disk is stable against a radial collapse. Besides, they pointed out that a massive-disk model requires unrealistically low viscosity, i.e. a large Reynolds number, and is likely to be dynamically unstable. In addition, they discussed remaining uncertainties in the knowledge of the nature and evolutionary stage of β Lyr, pointing out, for instance, that an ultimate proof of the mass transfer between the binary components is still needed.

Note that while Hubeny & Plavec's (1991) model was later used to a detailed modelling of the observed light curves (as discussed below), Wilson's (1981, 1982) one was not as yet. Obviously, such a test would be desirable since the original Wilson's (1974) model of a rotationally flattened disk, fitted to the observed optical light curves, resulted in a disk radius which somewhat exceeded the equatorial radius of the Roche lobe. It would be of interest to see whether the self-gravitating disk model would be able to avoid this problem *and* provide a good fit to the light curves as it is the case for Hubeny & Plavec's disk.

Mazzali et al. (1992) published a two-wind radiation-driven model for the atmospheric features of β Lyr observed in the far-UV spectra of the binary. They argued that the observed emission-line profiles can be grouped into two categories, corresponding to a 'hot' wind from *star 1* and to a cooler wind from *star 2*. Modelling the profiles with a 3-D hydrodynamical code, they concluded that the hot wind from polar regions of *star 1* has a terminal velocity of 1470 km s^{-1} and leads to a mass loss of 5×10^{-8} $M_\odot yr^{-1}$ while the wind from *star 2* has a terminal velocity of only 390 km s^{-1} and leads to a higher mass loss rate of 7×10^{-7} $M_\odot yr^{-1}$. Once again, these numbers should be taken with some caution since they are based on the assumption of Woolf's (1965) masses of 12 and 2 $M_\odot$. Besides, I see a rather principal problem with their model: The orbital RV curve of *star 2* has a full amplitude of 370 km s^{-1} and any wind lines associated with this star, having a terminal velocity below 400 km s^{-1}, should also exhibit orbital RV changes of a similar amplitude. In the contrary to this, the existing RV measurements of the Copernicus and IUE spectra of β Lyr show that no emission or P Cygni line follows the RV curve of a similar amplitude as the absorption lines of *star 2* - cf., e.g., Hack et al. (1977) or Aydin et al. (1988).

Harmanec (1992) presented further quantitative arguments in favour of a model of β Lyr assuming a Roche-lobe filling *star 2* and a massive (B0-2V) *star 1* hidden in a large accretion disk. In particular, he re-interpreted the red Si II absorption lines, studied by Skulskij and Topilskaya (1991) as the *shell lines* from the outer parts of the disk around *star 1*, maintaining their conclusion that their RVs properly reflect the orbital motion of *star 1*. He also adopted the view that the satellite lines arise from absorption of radiation of *star 2* by the outer parts of the disk around *star 1* at phases near the primary mid-eclipse and used their observed RVs to further quantitative tests of the proposed model.

Harmanec was probably the first to point out the problem with the interpretation of the 'B5 spectrum' as arising from a circumbinary envelope located in the orbital plane of the binary. At the end of the paper he writes: "Which medium within the system is responsible for the observed blue-shifted narrow absorption He I lines .... seen essentially in all orbital

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[2] Note that this conclusion contradicts the light curve modelling by Wilson (1974) and was abondoned by Hubeny himself in later studies discussed below

phases? I confess I am not satisfied with the standard interpretation in terms of a circumbinary envelope or outflowing spiral since it is very hard to see what can excite the He I lines *in the orbital plane and at a distance greater than some 50 $R_\odot$ from the binary components if the radiation field in the orbital plane is a combination of a B8 and ≈A5 spectrum.* I am afraid we will have to seek another location, perhaps in the stellar wind above the orbital plane or in jets which can "see" the radiation of *star 1*, although I have no simple explanation for the negative velocities observed (over 100 km s^{-1})."

Harmanec and Scholz (1993) carried out a very detailed radial-velocity study of β Lyr. They analyzed 1532 RVs of *star 2* and 33 RVs of *star 1*, collected from the astronomical literature and complemented by 83 RVs which they derived themselves. Their data span the time interval from 1892 to 1991.

The authors arrived at the following main results:

1. They confirmed an earlier conclusion by Klimek and Kreiner (1973, 1975) that a simple quadratic ephemeris is more appropriate to the description and future prediction of orbital phases of β Lyr than ephemerides based on cubic and higher terms in epoch which usually fail outside the time interval on which they were defined. Besides, they pointed out that for β Lyr individual epochs are derived more accurately from the clean RV curve of *star 2* with a large amplitude than from photometry. Indeed, the new ephemeris they derived from 99 years of spectral observations defines even the first observed light-curve minima in 1784 equally well as the best ephemerides based on photometric minima.
2. They confirmed that the orbit is circular to a high degree of accuracy.
3. They derived the most accurate orbital solution, defining the masses of both stars and their mass ratio of 4.49, which is usually adopted since then.
4. They were unable to find any compelling evidence for either a secularly variable systemic velocity of the binary or any other long-term changes in the residuals from the orbit or in times of minima. They demonstrated, however, a clear secular change in the RV of the metastable He I 3888 line.
5. They carried out the first direct test of the theory of large-scale mass transfer between the components, searching for the secular change of the semi-amplitude of the RV curve of *star 2* caused by the slowly changing mass ratio. They found such an effect in a good quantitative agreement with expectations but the associated error was too large to make the result conclusive.
6. They argued that the mass transfer between the binary components must be nearly conservative at present and estimated the mass transfer rate to be (2.09–2.19) $\times 10^{-5}$ $M_\odot yr^{-1}$, i.e. five times smaller than that required by the accretion-disk model by Hubeny and Plavec (1991).

Skulskij and Plachinda (1993) measured the Zeeman splitting of the red Si II lines of β Lyr using the Stokes-meter and CCD detector in the coudé focus of the Crimean 2.6-m reflector. They reported the presence of a weak magnetic field with a full amplitude of only 200 gauss in Si II 6347, and 400 gauss in Si II 6371 line. Although the reported errors are much smaller than the amplitudes of the complicated phase curves of magnetic-field intensity, my feeling is that the result requires an independent confirmation. The shape of the curves is quite peculiar and the two curves differ from each other.

Honeycutt et al. (1993) published observations of phase-locked variations of the strength and position of the Hα emission of β Lyr, based on automatic, unattended spectral observations. Regrettably, the observations are only presented in the graphical form and cannot be used to independent analyses.

Kondo et al. (1994) collected and analyzed the UV light curves of β Lyr down to 965 Å obtained by several astronomical satellites. They found a good agreement between the light curves obtained for the given wavelength by two or more different instruments. They also confirmed the finding that the depth of the secondary eclipse is growing with decreasing wavelength. At wavelengths below 1100 Å the object *does not exhibit* any phase-dependent light changes. OAO2 observations from 1970 and Voyager observations below 1100 Å seem to indicate some cycle-to-cycle variations. Kondo et al. conclude that the light variations in the UV wavelengths are affected by an optically thick circumbinary cloud which assumes a spheroidal shape at wavelengths below 1100 Å.

Berghöfer and Schmitt (1994) analyzed ROSAT all-sky survey observations and reported the discovery of X-ray emission from β Lyr and also from its visual companion β Lyr B. According to them, the observed X-ray luminosity of β Lyr is typical for a B0V star while the X-ray luminosity of β Lyr B is unexpectedly high.

The other end of the electromagnetic spectrum of β Lyr has also attracted growing attention. Jameson & Longmore (1976) obtained complete IR light curves at five passbands from 1200 nm to 8600 nm. They suggested that the gradual deepening of the secondary minimum with increasing wavelength could be explained by the presence of a plasma cloud around the secondary, with a temperature of 17500 K and extending to a distance of 23 $R_\odot$. Zeilik et al. (1982) obtained new IR light curves at five passbands from 1200 to 4600 nm and compared them to predictions of Wilson's disk model (Wilson 1974, Wilson & Lapasset 1981), arriving at fair though not perfect agreement. (Regrettably, they never published their observations.) Along with the improving quality of available radio telescopes, β Lyr was also observed at radio wavelengths. Already Wade and Hjellming (1972) discovered that β Lyr is a thermal radio source and estimated its radius to 50 AU, assuming the distance to β Lyr to be 500 pc. Jameson and King (1978) modelled the H II region around β Lyr, responsible for the radio emission, and concluded that it must be excited by a B2.5V or B5II star. Note, however, that the Hipparcos parallax implies a distance of 270 pc (Perryman et al. 1997) which makes the radio nebula about half the size of 50 AU. Leone et al. (1994) detected radio emission from β Lyr at 60 mm during their 1992 VLA radio survey of chemically peculiar stars.

There was an interesting development of the opinion about the secular stability of the optical light curve of β Lyr. As already mentioned, there were suggestions of cyclic changes of its shape, based on earlier photometric observations (cf., e.g., Blagg 1924, 1925, 1928 or Guthnick 1945). This view was opposed by Wilson (1974) who maintained that – apart from occasional disturbances near the centres of the eclipses – the light curve of β Lyr is reasonably consistent and symmetric, with only infrequent departures greater than a few hundreds of a magnitude.

Guinan (1989) analyzed his long and homogeneous series of photoelectric observations and found that the light curve of β Lyr varies in amplitude and shape, *including the light maxima*, with an apparent cycle of (275 ± 20) d. Van Hamme, Wilson and Guinan (1995) re-investigated several large sets of existing photometric observations, including a huge collection of Baxendell's visual observations from the years 1840-1877, reduced and published by Blagg (1924). They concluded that a period of $283^{\mathrm{d}}.39 \pm 0^{\mathrm{d}}.26$, with a good phase coherence, can consistently be detected in the O-C residua from all investigated orbital light curves. The semiamplitude of the 283-d variation was found to be about $0^{\mathrm{m}}.02$ for the majority of the data sets, including Baxendell's data.

I have some reservations to the use of visual observations to the determination of a more accurate value of the 283-d period, considering that the semiamplitude of the variation is $0^{\mathrm{m}}.02$ only. The plot of the residuals of Baxendell's observations vs. time (cf. Fig. 6 of Van Hamme et al. 1995) shows that the length of his typical observing season was comparable to the 283-d period. During each observing season the star was necessarily observed at different positions in the sky and the differential extinction and apparent colour variations had to be at least comparable to the amplitude of the 283-d change. Note that Baxendell used as many as ten different comparison stars, some of them of spectral types as late as K0. Actually, Van Hamme et al. themselves mention that periodic signals close to one tropical year (specifically the periods of $360^{\mathrm{d}}.9$ and $340^{\mathrm{d}}.0$) had much higher amplitudes than the signal at 283d in their periodograms of Baxendell's and also Luizet's visual observations. (Note also that Peel 1997 reanalyzed Luizet's data and argued in favour of the reality of the 340-d period, pointing out that 283-d and 340-d periods are both sub-multiples of a period of 3400d, similar to the one considered already by Blagg 1924.) The above-mentioned effects inevitably interfere with real 283-d variability present in visual observations and may affect the resulting value of the 283-d period in the period analyses of these data.

There is also another problem with the 283-d period. As seen in the residual plots for photoelectric observations, presented by Van Hamme et al. (1995), the scatter along the apparent 283-d curve remains high, nearly comparable to the amplitude of the changes. This may indicate that the apparent 283-d period is only a beat period of some much more rapid variations with the orbital period of the binary (see also the results of a study by Harmanec et al. 1996 on this issue, mentioned below).

De Greve and Linnell (1994) used the improved physical properties of β Lyr from the papers by Hubeny and Plavec (1991) and Harmanec and Scholz (1993) and attempted to calculate sequences of evolutionary models, including the stages of large-scale mass-exchange, to find out a probable progenitor of β Lyr. They concluded that at present β Lyr is approaching the end of the mass transfer stage and that it has evolved in a mildly non-conservative way (i.e. with some, but rather small mass and angular momentum loss) from an initial pair of stars of 9 M$_\odot$ and 7.65 M$_\odot$. They found a good agreement with the observed properties of β Lyr at an evolutionary age of 31.9 millions of years from the ZAMS. They confirmed that the mass transfer brought the layers affected by nuclear burning to the surface of the mass-losing star. They also found a mass transfer rate which agrees well with the rate estimated by Harmanec and Scholz (1993). As the authors remind the reader, the mass and angular momentum loss are kept constant during the whole stage of mass exchange in their calculations which is a rather crude approximation of a real situation. One would expect that the rate of *mass loss* from the system should depend on the rate of the *mass transfer* between the components which varies very dramatically during the mass-exchange process. On the other hand – considering that only mild mass and angular momentum loss was needed in the modelling by De Greve and Linnell (1994) – it is clear that their evolutionary model sequence is a large step towards a realistic description of the process.

Since more accurate data are available now, I decided to re-consider the age problem found by Dobias and Plavec (1985). I adopted the effective temperature of 14250 K for β Lyr B = HD 174664 which they derived from their spectra, i.e. log T_{eff} = 4.154. Adopting the mean UBV values of β Lyr B from Mermilliod's electronic database held at the Geneva Observatory

V=$7^{\mathrm{m}}.22$, $B-V$=$-0^{\mathrm{m}}.08$, $U-B$=$-0^{\mathrm{m}}.49$,

and applying a standard dereddening, I obtained

V_0=$7^{\mathrm{m}}.017$, $(B-V)_0$=$-0^{\mathrm{m}}.143$, $(U-B)_0$=$-0^{\mathrm{m}}.535$.

Using the dereddened visual magnitude and the Hipparcos parallax of $0''00370 \pm 0''00052$ derived for β Lyr (β Lyr B has not been observed by Hipparcos), I arrive at the radius of β Lyr B of 2.71 R$_\odot$ (2.38-3.16 R$_\odot$ if the range of parallax uncertainty is considered). The bolometric magnitude of β Lyr B is then -$1^{\mathrm{m}}.34$, smaller than the value of -$1^{\mathrm{m}}.9$ derived by Dobias and Plavec.

Note that the dereddened UBV values as well as the effective temperature consistently indicate a spectral type slightly earlier than B6 for β Lyr B. Dobias and Plavec estimated the mass of the star from the line profiles but such a technique can lead to rather large uncertainties. Using the relation between effective temperature and stellar mass and radius, based on accurate determinations via eclipsing binaries, after Harmanec (1988), one gets 2.83 R$_\odot$ and 3.9 M$_\odot$. This is also consistent with the above values. More importantly, comparing the values of effective temperature and bolometric magnitude adopted here for β Lyr B and comparing them either with Fig. 8 of Dobias and Plavec (1985) or with corresponding evolutionary models by Claret and Giménez (1992), one can see that the age problem is no longer there.

Mourard et al. (1992) observed β Lyr with the large optical spectro-interferometer GI2T and were able to resolve partly the emission-line structure in the Hα line. Encouraged by this finding, the French GI2T group an I have organized a dedicated observing campaign on interferometric, spectral and photometric observations on β Lyr in 1994, in an effort to resolve the binary and to understand the geometry of the circumstellar matter. The campaign was very successful: Spectro-interferometry near the Hα and He I 6678 lines was obtained on 11 nights at different orbital phases and 330 new electronic spectra and 229 new UBV, $UBVRI$ or V photoelectric observations were accumulated. The analyses of the new and critically re-examined older data obtained by other investigators were published in a detailed study by Harmanec et al. (1996) and led to the following principal findings:

1. The bulk of the Hα and He I 6678 emissions does not originate in either the accretion disk or circumstellar envelope as usually assumed in the previous studies but in jet-like structures, perpendicular to the orbital plane and centred on the probable region of the interaction of the gas stream and the accretion disk around *star 1*. Also the blueshifted absorption lines (the "B5 spectrum") could be naturally understood as originating from self-absorption in one of the jets, their actual outflow velocities thus being comparable to typical wind velocities of hot stars.
2. An analysis of the V light curve, based on 2852 homogenized data spanning an interval of 36 years showed that the residuals from the mean light curve could be reconciled with the $282\overset{\mathrm{d}}{.}4 \pm 0\overset{\mathrm{d}}{.}07$ period, significantly different from the $283\overset{\mathrm{d}}{.}39 \pm 0\overset{\mathrm{d}}{.}26$ period found by Van Hamme et al. (1995). However, the scatter along the 282-d residual light curve is clearly larger than the expected observational errors. Investigation of appropriate data subsets revealed that the amplitude and phase of the 282-d variation vary with the orbital phase, virtually disappearing near one elongation and during the secondary minimum.
3. Line-profile variations of the Hα and He I 6678 lines on a time scale shorter than one orbital period were also found. Their possible periodicity of about $4\overset{\mathrm{d}}{.}7$ seems to be causally related to the orbital and 282-d period.
4. The binary itself was not resolved via inteferometry and this may indicate that the projection of the binary orbit onto the sky is roughly perpendicular to the North-South orientation of the only baseline of the GI2T interferometer.

The jet-like structures were independently discovered from ultraviolet and visual spectropolarimetry by Hoffman et al. (1998) (see also the preliminary report by Nordsieck et al. 1995). They were able to detect the structures via a large change of the polarization angle in the Balmer emission lines and near-UV continuum. They also found that the intrinsic polarization in the optical part of the spectrum shows eclipses and is associated with material near the accretion disk.

Linnell and Hubeny (1996) suitably combined their computer programs and developed what they called the BINSYN suite: a set of light synthesis and spectrum synthesis programs for binary stars with optically thick accretion disks. Linnell, Hubeny and Harmanec (1998) applied that set of programs to model the optical light curve of β Lyr (based on the data accumulated and homogenized by Harmanec et al. 1996), the satellite UV light curves published by Kondo et al. (1994) and the continuum energy distribution from the IUE observations. They confirmed an earlier conclusion by Wilson (1974) that any configuration in which a small polar segment of *star 1* would be directly visible would lead to an observable dip in the secondary eclipse which, however, is not observed. They were unable to find any plausible model which would satisfy both, the observed light curves and the continuum energy distribution at the same time. They suggested that the solution could be to postulate the presence of a scattering region above the poles of *star 1*, possibly associated with the jets.

Bisikalo et al. (2000a, 2000b) calculated gasdynamical models of mass exchange between the components of β Lyr for the best available system properties. They found that the interaction of the gas stream when it encircles the mass-accreting *star 1* with the initial stream flowing from *star 2* leads indeed to the formation of jet-like structures and found a very satisfactory agreement between the theoretical position of the region of interaction and the position deduced by Harmanec et al. (1996) from the observed data. They also analyzed electronic spectra of the star to confirm the orbit of *star 1* based on the pair of red Si II lines.

So far the final confirmation of the presence of jet-like structures in β Lyr came from a recent study by Umana et al. (2000) who observed β Lyr with a radio interferometer network MERLIN and resolved the radio nebula around the binary. They found that the nebula is very nearly aligned with the optical jet-like structures. Somewhat surprisingly, however, they conclude that the radio emission comes from the wind emanating from *star 2* which is ionized by the radiation of *star 1*. They estimated the brightness temperature of the nebula to (11000 ± 700) K and its overal extent to 40 AU. They also pointed out that their observations constitute an ultimate proof that some mass is being lost from the binary during the mass transfer process. In particular, they estimated that 0.015 $M_\odot$ had been lost from the binary since the onset of the mass transfer. (Note that the theoretical value, based on the non-conservative mass-exchange models of β Lyr by De Greve and Linnell 1994 is 0.47 $M_\odot$.)

It appears, therefore, that the canonical picture of β Lyr with the accretion disk as the main component of its circumstellar gaseous structures was not complete and has to be enriched for another important item: the jet-like structures. Clearly, these structures markedly affect some important observed properties of the binary and must be considered in all future attempts to develop a consistent model of the binary.

Harmanec (1999) once more tried to carry out a direct test of the theory of large-scale mass exchange, first attempted by Harmanec and Scholz (1993), complementing their set of RVs by numerous new RV observations accumulated since then (including the RVs obtained during the commissioning run with the new echelle spectrograph Traficos at Tautenburg and published by Hildebrandt et al. 1997). Once again, the result was inconclusive. Harmanec also demostrated that there is no hope to detect the change of the Roche lobe, presumably filled by *star 2*, due to changing mass ratio from a small secular brightness variation of the binary at light maxima. He estimated that the effect amounts to only a few $0^{\mathrm{m}}\!.0001$ per century.

Kreiner et al. (1999) fitted a parabola to the O-C deviations of all available observed photometric minima of β Lyr from a linear ephemeris and analyzed the residuals from that parabolic fit for periodicity. They were able to detect a period of $283^{\mathrm{d}}\!.5 \pm 0^{\mathrm{d}}\!.1$ with an amplitude modulation of $0^{\mathrm{d}}\!.052 \pm 0^{\mathrm{d}}\!.008$ in the residuals *from the primary minima only*. No such clear periodicity was found in the residuals from secondary minima. This – in a sense – corroborates the findings by Harmanec et al. (1996). Kreiner et al. briefly discussed the possible causes for such a periodicity and concluded that it could be related to a cyclically variable mass transfer between the binary components.

Wilson and Van Hamme (1999) re-analyzed available epochs of minima and RVs used by Harmanec and Scholz (1993) to search for evidence of a small eccentricity of the orbit of β Lyr and for associated apsidal motion and also to a general search for periodicity. They were unable to find any statististically significant periodicities of the O-C residuals from the times of photometric minima but they detected 8 possible periods in the RV residuals, ranging from 28 to 257 days. They tentatively suggested that these periodicities may indicate presence of other orbiting stars in the system. They were unable to find any direct evidence of a real eccentricity of the orbit but claim that eccentricities slighly smaller than 0.01 cannot be ruled out. They also discussed several possible explanations for the 283-d periodicity. Developing a quantitative model to investigate possible disk precession and apsidal motion, they concluded that the 283-d period is too short to be caused by the apsidal motion and that it cannot be due to precession of the disk. They tentatively suggested that the period could be related to disk pulsations caused by impulsive mass transfer each periastron passage. This explanation requires the existence of at least slightly eccentric orbit and remains hypothetical until future accurate data will allow more stringent tests on the real shape of the binary orbit.

Linnell (2000) made another attempt to model the light curves and continuum energy distribution of β Lyr with the help of a model which includes a thick accretion disk. He pointed out that:

- no isothermal disk rim model can represent the observed UBV *and* OAO2 light curves, and
- the width of the secondary minimum in all observed light curves indicates that the hot continuum source must be coextensive with the accretion disk rim.

He was able to obtain good fits to the UBV and OAO2 light curves and fair fits to spectrophotometric scans using an empirical two-temperature model. However, he found that the model fails to predict the height of the Balmer jump and the light curves observed in the infrared (IR) parts of the spectrum. He again argued that a scattered hot radiation from *star 1* must be included in the modelling. He also specifically pointed out the problem of too low mass transfer rate and suggested that the radiative energy of *star 1* significantly contributes to the observed properties of the accretion disk.

4. Current picture of β Lyr and what remains to be understood

The reader – even if he or she is well acquainted with the problems of interacting binaries – may be bewildered by the complexity of β Lyr and by the large number of various attempts to model it. Therefore I conclude this critical review by presenting my own current picture of it. To facilitate imagination, I present in Fig. 1 an artist's view of the binary and its circumstellar structures at two orbital phases.

4.1. Basic physical elements of β Lyr

Seen in the sky, β Lyr consists of as many as six optical components β Lyr A (the binary) to β Lyr F but only β Lyr B and β Lyr F are gravitationally bounded to β Lyr A. The binary is at a distance of (270 ± 39) pc from us.

The binary is formed by an early B dwarf and a bright giant of spectral class B6-8 (called *star 1* and *star 2* throughout this review). The orbital period has been increasing at a rate of 19 sec per year. Its value was $12^{\mathrm{d}}\!.893$ in 1784 and is close to $12^{\mathrm{d}}\!.94$ these years. *Star 2* has a well-defined RV curve which is basically sinusoidal but shows clear signs of the rotational effect. This is related to the fact that *star 2* is filling its critical Roche lobe and sending the gaseous material towards *star 1*. *Star 1* is completely hidden from view by a thick accretion disk. This star may be rotationally distorted but we have no direct evidence of its shape. Only from analogy with less complicated systems we can conclude that *star 1* is a basically normal early-type B star with properties corresponding to its inferred mass. Considering estimates based on high-dispersion spectra (Harmanec and Scholz 1993, Harmanec et al. 1996 and Bisikalo et al. 2000b), one can take

$$K_1 = 42.0\,\mathrm{km\,s^{-1}} \text{ and } K_2 = 186.3\,\mathrm{km\,s^{-1}} \tag{1}$$

as representative semiamplitudes characterizing the orbital motion of the binary components. This implies

$$a_1 \sin i \;=\; 10.74\,\mathrm{R}_\odot,\;\; M_1 \sin^3 i = 13.0\,\mathrm{M}_\odot, \tag{2}$$

$$a_2 \sin i \;=\; 47.64\,\mathrm{R}_\odot,\;\; M_2 \sin^3 i = 2.93\,\mathrm{M}_\odot. \tag{3}$$

Observers on the Earth see the binary orbit nearly edge-on. Probably the best current estimate of the orbital inclination, based on the light-curve modelling, is $i = 86°$ (Linnell et al. 1998, Linnell 2000). This agrees well with an earlier determination of 85° by Wilson and Lapasset (1981). This inclination implies the current separation of the centres of both stars

$$A = 58.52\,\mathrm{R}_\odot \tag{4}$$

(note that in 1784 it was $58.31\,\mathrm{R}_\odot$ due to at that time shorter orbital period) and the most probable basic physical properties of both stars, listed in Table 1. The radius of *star 2* is given by the dimensions of the corresponding critical Roche lobe. Note that the reasonable assumption of spin-orbit synchronization for *star 2* implies $v \sin i$ = 57.4 km s^{-1}, well within the range of directly derived values. The equatorial radius of the Roche lobe around *star 1* (perpendicular to the line joining the two components) is 30.3 $\mathrm{R}_\odot$.

Complicated observed spectrum of β Lyr is caused by the presence of two dominant structures of circumstellar matter:

Table 1. Macroscopic properties of the binary components of β Lyr

Element	*star 1*	*star 2*
Mass ($M_\odot$)	13.1	2.96
Radius ($R_\odot$)	6::	14.68
$T_{\rm eff}$ (K)	28000::	13000
$v \sin i$ (km s^{-1})	?	55 ±10

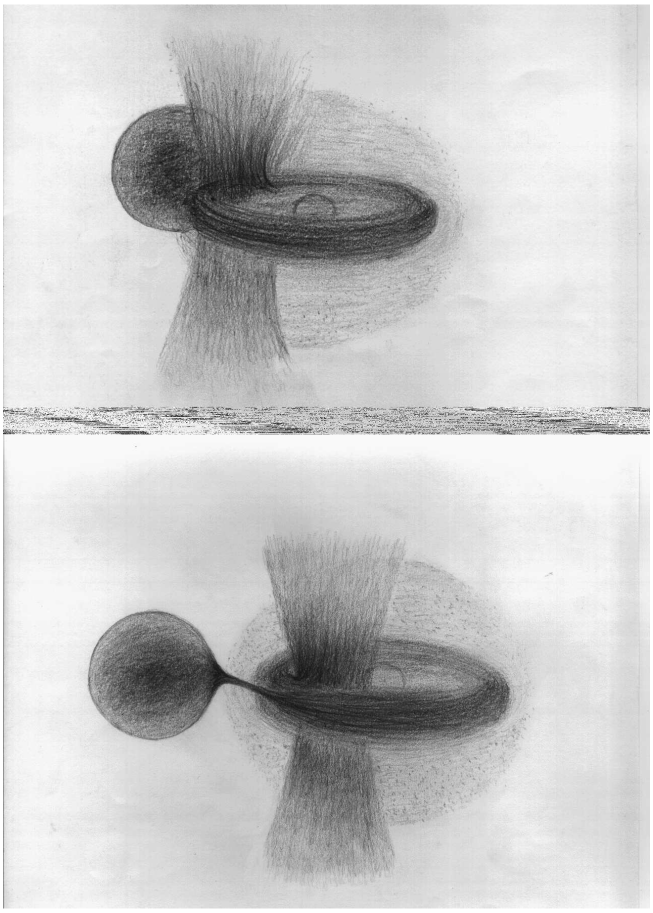

Fig. 1. An artist's view of the probable appearance of β Lyr system with various components of its circumstellar matter: gas stream, accretion disk, jet-like structures and scattering halo/stellar wind above the polar regions of the mass-accreting star. A view at elongation and at a phase shortly after the primary mid-eclipse are shown. All relative dimensions are drawn in scale. The position of the mass-accreting star is indicated, although the star is in fact hidden from view inside the disk

accretion disk around *star 1* and jet-like structures perpendicular to the orbital plane and emanating from an area of gas-stream interactions in the disk.

The disk has probably negligible mass but is optically thick in the continuum, simulating a kind of a pseudophotosphere. Its edge, which is directly observable, is relatively cool and appears to us as something like an A5III spectrum. The radiative energy of the disk comes partly from the mass accretion but a significant part of it must also come from reprocessed radiation of the central star. The disk is also redistributing the radiation of *star 1* away from the orbital plane, making *star 1* to appear underluminous for its mass. The fact that *star 1* is not directly observable implies that the thickness of the disk perpendicularly to the orbital plane must be at least 6 $R_\odot$. The disk is the main component responsible for the unusual character of the observed light curve.

The jet-like structures certainly emanate from an area which is offset with respect to the line joining the two stars but there must also be a strong hot wind from the polar regions of *star 1* and it is probable that what we observe is a combination of these two structures. They are responsible for the bulk of the observed line emission and also for the blue-shifted absorption lines typical for temperatures of 20 000 K or more. In the UV and IR/radio parts of the electromagnetic spectrum, the gaseous material away from the orbital plane manifests itself to large distances from the binary and may contribute also to continuum radiation at these wavelengths and be responsible for the interchange of the relative depths of the eclipses and their gradual disappearance in the far-UV regions.

Although the gas stream between the components plays a crucial role in the evolution and current appearance of the system, it remains practically unobserved since its own dimensions and radiation are neglibible in comparison to the Roche-lobe filling *star 2*, disk and jet-like structures. Besides, the stream is obscured by these structures and stellar bodies during a large part of the orbital cycle.

The present β Lyr has evolved via large-scale mass exchange from a binary with much shorter orbital period than the current one. The Roche-lobe filling *star 2* was initially the more massive of the two. The difference between β Lyr and the classical Algol-type semi-detached binaries is that while the latter are in the very slow final stages of mass exchange (typical $\dot{M}$ of about 10^{-9} $M_\odot$ yr^{-1}), β Lyr is only ending the initial rapid stage of the mass transfer, still having a high mass transfer rate of 2×10^{-5} $M_\odot$ yr^{-1}. This explains why the circumstellar structures around β Lyr are so spectacular in comparison to Algols. Since there is a statistically much larger chance to observe a binary in the longest final slow stage of the mass exchange than during the short rapid stage, this also explains why systems similar to β Lyr are so rare.

4.2. Open problems

In spite of large progress during last two decades, there are still many things, related to β Lyr, which need to be addressed. They include:

1. A fully consistent model of the phase-locked changes of the light and colour variations, including the variations of the shape of the observed electromagnetic spectrum.
2. Explanation of rapid spectral changes and their possible relation to orbital and long-term changes.
3. A conclusive proof of the presence or absence of a macroscopic magnetic field associated with one of the binary components.
4. Understanding the character and nature of the long-term spectral changes of emission lines.
5. Direct imaging of the bodies and structures present in the system. This dream may turn to reality soon, with the new generation of powerful interferometers becoming operational.

I end this (certainly incomplete) list of open problems with the wish that β Lyr will soon attract yet another generation of talented young astronomers coming to the field and that thanks to them she will give up on a few more of her secrets.

Acknowledgements. I appreciate useful comments and a careful proofreading of the draft version of this paper by Drs. I. Hubeny, A.P. Linnell and M.J. Plavec. Thanks are due to Ms. Alexandra Kalašová who has drawn Fig. 1 at my request. The paper profitted, both in the content and style, from detailed careful comments, critical remarks and useful suggestions by the referee, Dr. R.E. Wilson. I also acknowledge the use of the NASA Astronomical Data System bibliography and SIMBAD bibliography maintained at the Centre of Astronomical Data in Strasbourg. This study was supported from the research plans J13/98: 113200004 and K2043105.

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