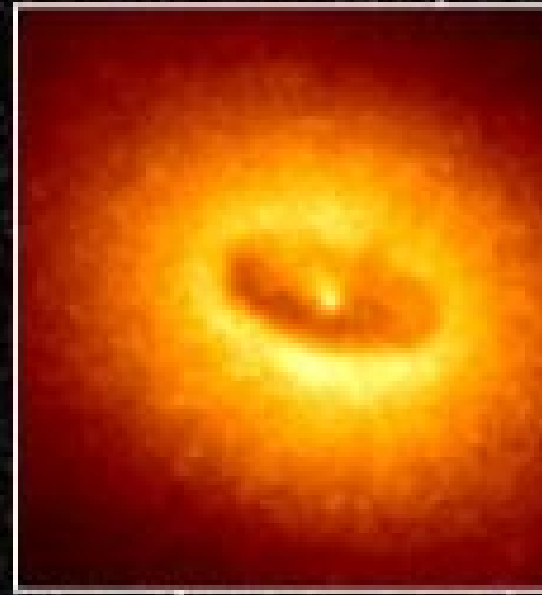


Multi-Technique Study of the X-Ray Binary Cyg X-1

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Abstract

- The results based on our many-year optical photometric, high-resolution spectral and spectropolarimetric observations by using the tools of different kinds are briefly reviewed.
- The main optical photometric variation component is the ellipsoidality effect been studied in details in Roche model. Apart from different kinds of flares, dips and “precession” period 147/294 d were revealed. Evidence of irregularities in matter flowing from one component to another was detected.
- Cross-correlation analysis revealed lags of X-ray (2-10 keV) long-term variations in respect to the optical ones. It allowed determining accretion time which is much shorter than that in standard accretion model.
- The comparison of the observed spectra with non-LTE model ones allowed us to set limits on the O-supergiant Cyg~X-1 optical component $T_{\text{eff}} = 30400 \pm 500 \text{K}$, $\log g = 3.31 \pm 0.07$ and the element overabundances: from 0.4 dex to 1.0 dex for He, N, Ne, Mg, Si, that is, the elements affected by CNO- and alpha-processes. Tidal distortion of Cyg X-1 optical component and its illumination by X-ray emission of the secondary are taken into account.
- The photometric and spectral variations point to the supergiant parameters' changes on the time scale of tens of years. Line profile non-LTE simulations lead to the conclusion that the star radius has grown about 1-4% from 1997 to 2003-2004 while the temperature decreased by 1300-2400K.
- The spectral line profile sets permitted us to construct the binary 2D and 3D tomographic maps. The comparison of 2D tomographic map with the theoretical calculations allowed to construct a more precise system model and receive better information on the gas flowing. The hard limits on Cyg~X-1 component mass ratio were obtained by such manner:
 $1/4 \leq M_X/M_O \leq 1/3$.
- Our VLT 8-m telescope spectropolarimetric observations permitted us to reveal the magnetic field of ~100 G on the supergiant and to suspect the magnetic field of ~600 G on the accretion structure outer limit. For the first time the existence of magnetic accretion on the black hole has been confirmed.

Brief review of our 36-year Cyg X-1 study by using multi-technique methods and based on our optical photometric, high-resolution spectral and spectropolarimetric observations.

Here the most of **Key topics** of this conference is presented:

- Multiwavelength photometry and spectroscopy of interacting binaries
- Imaging techniques: adaptive optics, interferometry, polarimetry, tomography
- Model atmospheres of stars, interacting binaries, disks, exoplanets, and brown dwarfs
- Synthetic light curves, velocity curves, spectra of binary stars, and spectra of accretion structures

Scheme of X-Ray Binary Cyg X-1

$P_{\text{orb}} = 5.6^{\text{d}}$ $P_{\text{prec}} = 294^{\text{d}}$

scattering gas

hot line

black hole

$M_{\text{x}} = 7-20 M_{\text{O}}$

accretion disc

$L = 4\% L_{\text{tot}}$

jet

hot spot

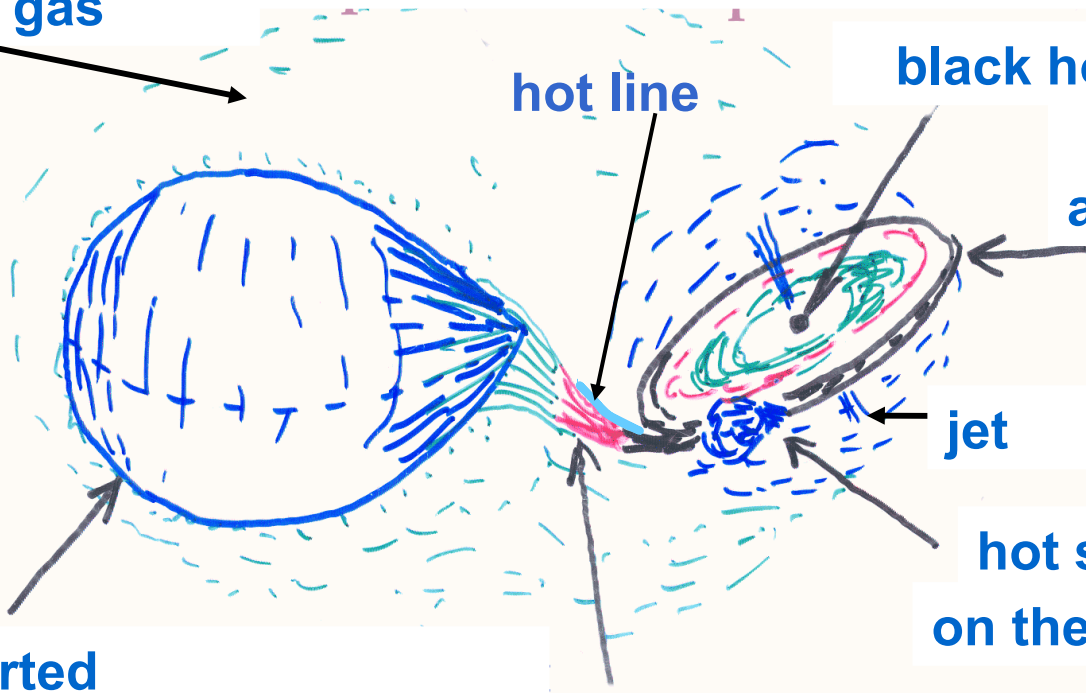
on the disc $L = (0-4\%) L_{\text{tot}}$

tidally distorted

supergiant O9.7 Iab
 $M_{\text{O}} = 20-60 M_{\text{O}}$ $L = 95\% L_{\text{tot}}$

collimated stellar wind
 -- accretion stream

Distance $d = 1.8-2.5$ kpc



Multiwavelength photometry

Photometric observations and comparison with X-ray data

The main results are reported in:

- Karitskaya E.A., Goranskij V.P., Grankin E.N. et al.: 2000, Astronomy Letters, 26, 22. (Pis'ma v Astron.Zh., 26, 27);
- Karitskaya A.A., Voloshina I.B., Goranskij V.P. et al.: 2001, Astron.Rep., 45, 350.(Astron.Zh., 78, 408);

In the frame of the international campaign "Optical Monitoring of Unique Astrophysical Objects" (Georgia, Kazakhstan, Russia, Uzbekistan, and Ukraine) in 1994-1998:

- 2258 UBV_R observations made during 407 nights 1994-1998.
- Comparison with ASM/RXTE (1.3-12 keV) 1996-2001 data – 1806 daily points

By comparing Cyg X-1 photoelectric (UBVR) and X-ray variations we found:

- variability - different kinds of flares, dips and “precession” period 147/294 d;
- a correspondence between optical and X-ray variations.

Cross-correlation analysis of the X-ray and optical mean brightness shows significant correlation. The X-ray variations delays in respect to the optical one - **7 d delay in 1996 and 12 d - in 1997-1998** (the main 1996 X-ray outburst and the mean orbital optical and X-ray light curves were subtracted from the X-ray and optical data).

For 1997-1998 we derived a correlation, with the X-ray light curve lagging **12 +/- 2 days** relative to the optical light curve, with a **significance** level substantially **exceeding 99.99%** (Karitskaya et al. 2001).

- **Evidences of accretion instability**

Evidences of accretion instability

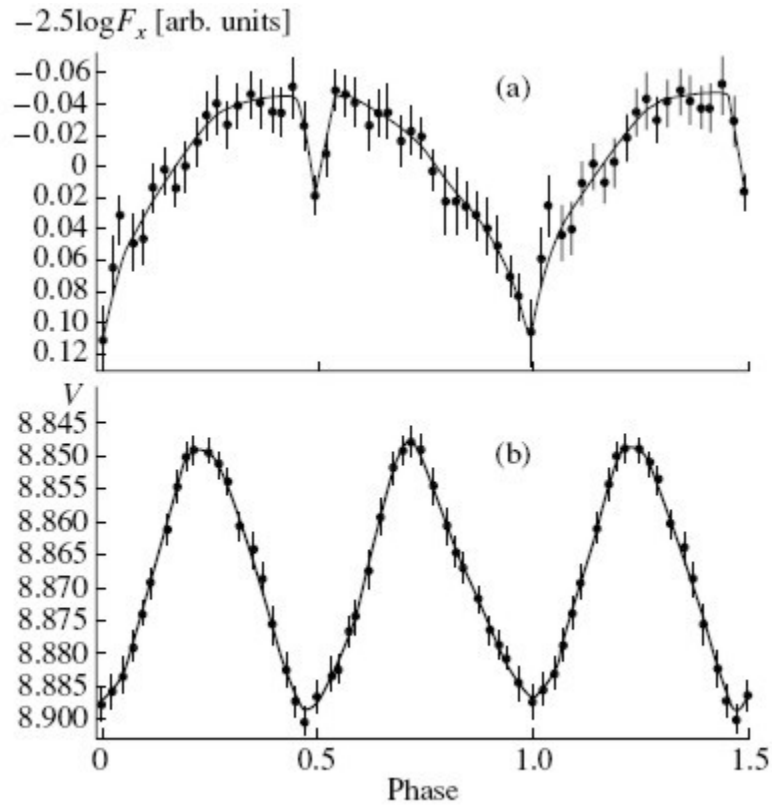
- 1. The shape variations of X-ray orbital light curve.
- 2. Unusual optical deep fading in November, 1996.
- 3. Several-day-long optical flares coincided with X-ray dips.

The suggested scenario of flares and dips

Sometimes the matter flows, in separate portions, from the supergiant on to the accretion structure. Each portion creates a shock wave and a gas bulk which give rise to a powerful **several-day-long optical flare**. The gas ejected into the surrounding space absorbs soft X-rays, thus causing an **X-ray dip**. The rest of the matter, after the time-interval it needs to travel through the accretion structure (disk), gives rise to an X-ray flare.

The characteristic time of the matter transfer through the accretion disk was about 7 days in Summer and Autumn 1996 and 12 days in 1997-98.

The orbital light curves $P=5.6$ d



$A=0.045 \pm 0.002$ mag

$A=0.003 \pm 0.002$ mag

The ellipsoidality effect-ROCHE model-admissible parameter values for Cyg X-1

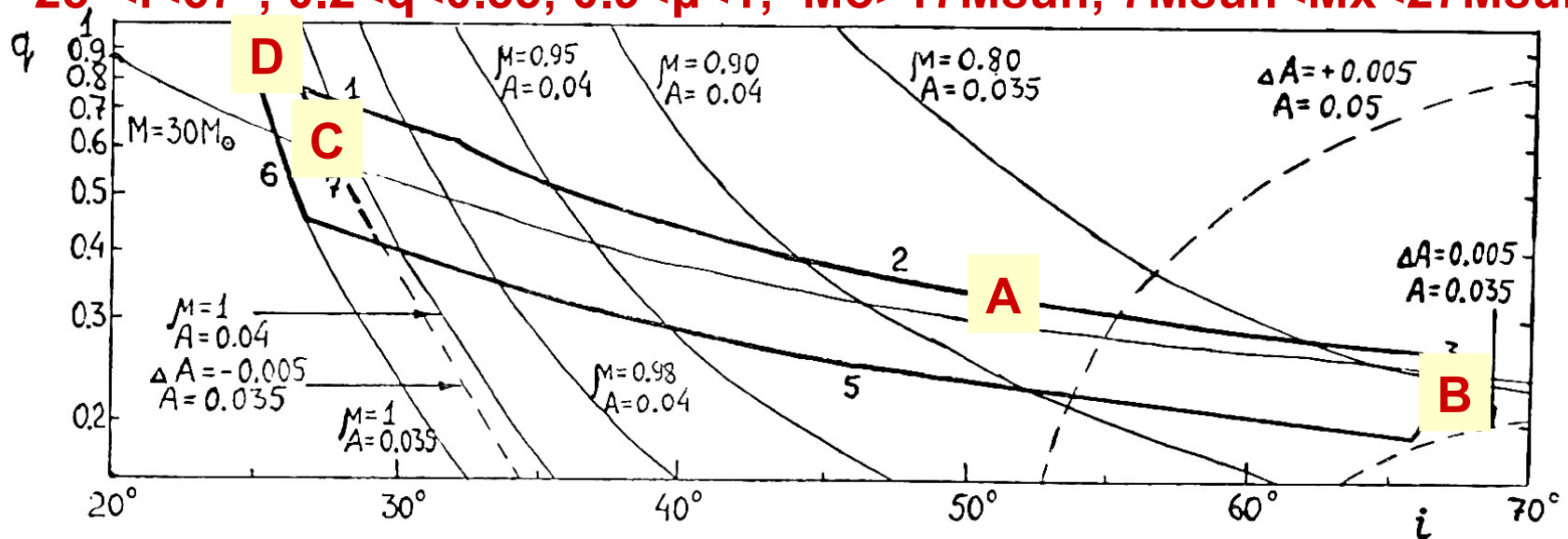
•36 years ago in our paper

Bochkarev N.G. Karitskaya E.A., Shakura N.I., Soviet Astronomy Letters, vol. 1, 1975, p. 118-120:

for $A = 0.035 - 0.050^m$, $A < 0.005^m$, $d > 2\text{kpc}$, $T_{\text{eff}} < 35000\text{ K}$

the admissible values of Cyg X-1 parameters were obtained:

$25^\circ < i < 67^\circ$; $0.2 < q < 0.55$; $0.9 < \mu < 1$; $M_0 > 17M_{\text{sun}}$; $7M_{\text{sun}} < M_x < 27M_{\text{sun}}$



i

A-D

q

J.A.Orosz et al.

Distance to Cyg X-1

In our paper

Bochkarev N.G., Karitskaya E.A., **Cyg X-1 (V1357 Cyg) and its interstellar environment**, Astrophysics and Cosmology After Gamow, edited by G. S. Bisnovaty-Kogan, S. Silich, E. Terlevich, R. Terlevich and A. Zhuk. Published by Cambridge Scientific Publishers, Cambridge, UK, 2007, p.395

ISM absorption localization toward Cyg X-1 was investigated. As a result we renew distance limits. 3D-velocity vector and ISM spatial distribution reconstruction permit us to limit black hole age and birth place. Two probability:

- 1) **$d \sim 2.3$ kpc** - Cyg X-1 born in CygOB3 association (not more than 8 Myr ago) –
 - no kick effect from black hole creation
 - velocity is about 0
- 2) **$d \sim 1.8$ kpc** - Cyg X-1 born in CygOB1 association (not early than 7.5 Myr ago) –
 - kick effect from black hole creation velocity ~ 20 km/s

Reid M.J. et al Astro-ph 1106.3688 (June 2011) by using trigonometrical parallax in radio (VLBI measurement) obtained **$d = 1.75 - 1.98$ kpc and velocity ~ 21 km/s** – so Cyg X-1 was born more than 7.5 Myr ago in CygOB1.

In the case of short scale of distances in Galaxy ($R_G = 7.5$ kpc) the distance to CygOB3 association **$d \sim 1.8$ kpc** - Cyg X-1 was born in CygOB3 not more than 8 Myr ago.

The spectroscopy of Cyg X-1 since 2002 up to now

The main tasks and prospect of high-resolution spectroscopy of Cyg X-1 are published in the paper:

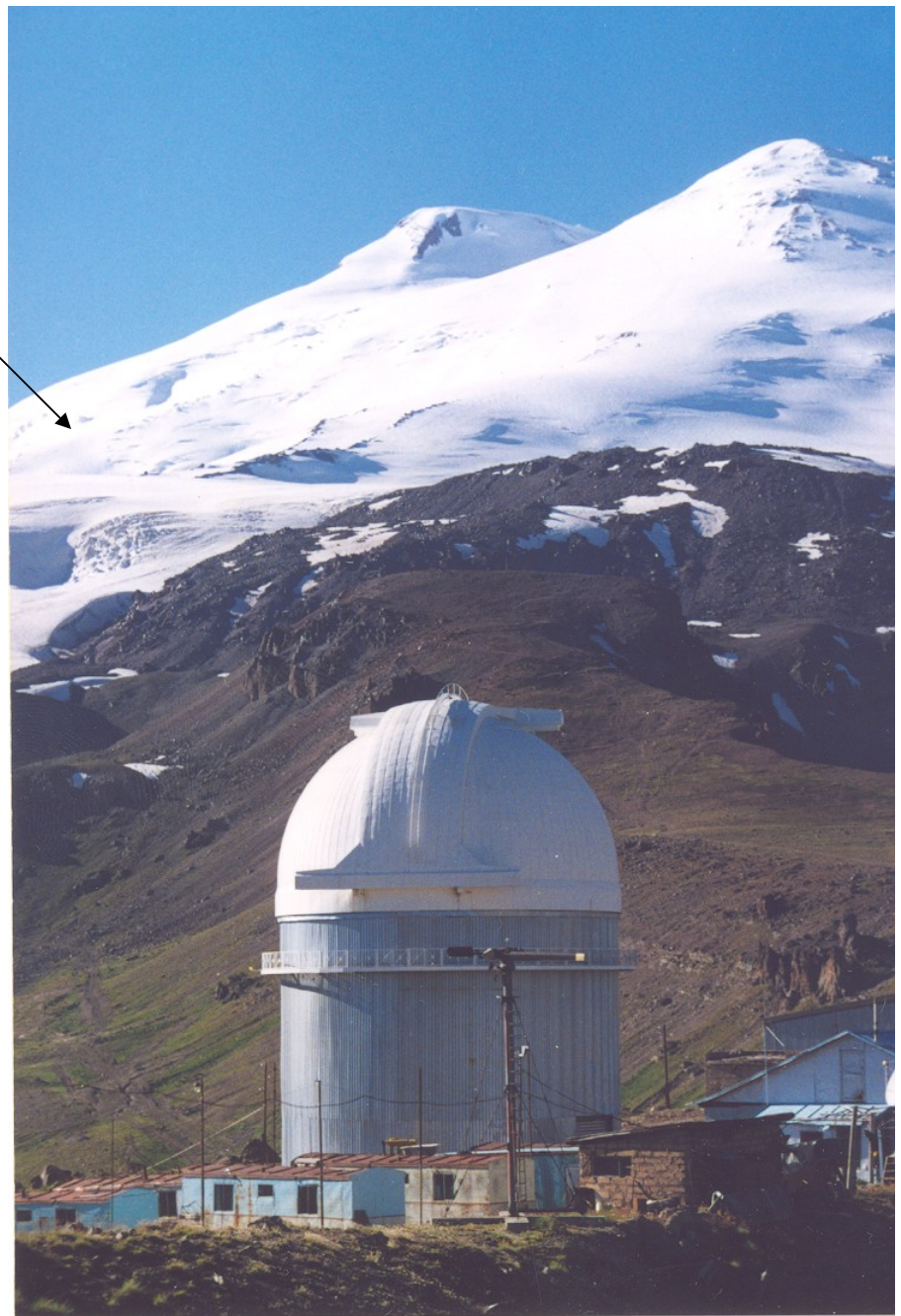
- E.A.Karitskaya, Kinematika i Fizika Nebesnykh Tel, Suppl. No.4 230-233 (2003).

The main high-resolution precision spectroscopy of Cyg X-1 our results are published in the paper:

- Karitskaya E.A.; Bochkarev, N. G.; Bondar', A. V.; Galazutdinov, G. A.; Lee, B.-C.; Musaev, F. A.; Sapar, A. A.; Shimanskii, V. V., Spectroscopic Monitoring of V1357 Cyg = Cyg X-1 in 2002–2004, Astronomy Reports, Volume 52, Issue 5, pp.362-378, (2008).
- E.A.Karitskaya, M.I.Agafanov, N.G.Bochkarev, A.V.Bondar, G.A.Galazutdinov, B.-C.Lee, F.A.Musaev, O.I.Sharova, V.V.Shimanskii, A.E.Tarasov. Results of high-resolution optical spectroscopy investigation of Cyg X-1 = V1357 Cyg, Astronomical and Astrophysical Transactions, v. 26, p. 159-162 (2007)

High-resolution spectral observations of 2002-2004

- Peak Terskol Observatory (Central Caucasus, Russia):
2-m telescope
echelle-spectrographs:
 - Coude Focus:
 $R = 45000, 3700 - 10300 \text{ \AA}$;
 - Cassegrain Focus:
 $R = 13000, 3800 - 7600 \text{ \AA}$.
- BOAO Observatory (South Korea):
1.84 m telescope
fiber echelle-spectrograph:
 $R = 44000 \text{ \& } 30000, 3800 - 10000 \text{ \AA}$.

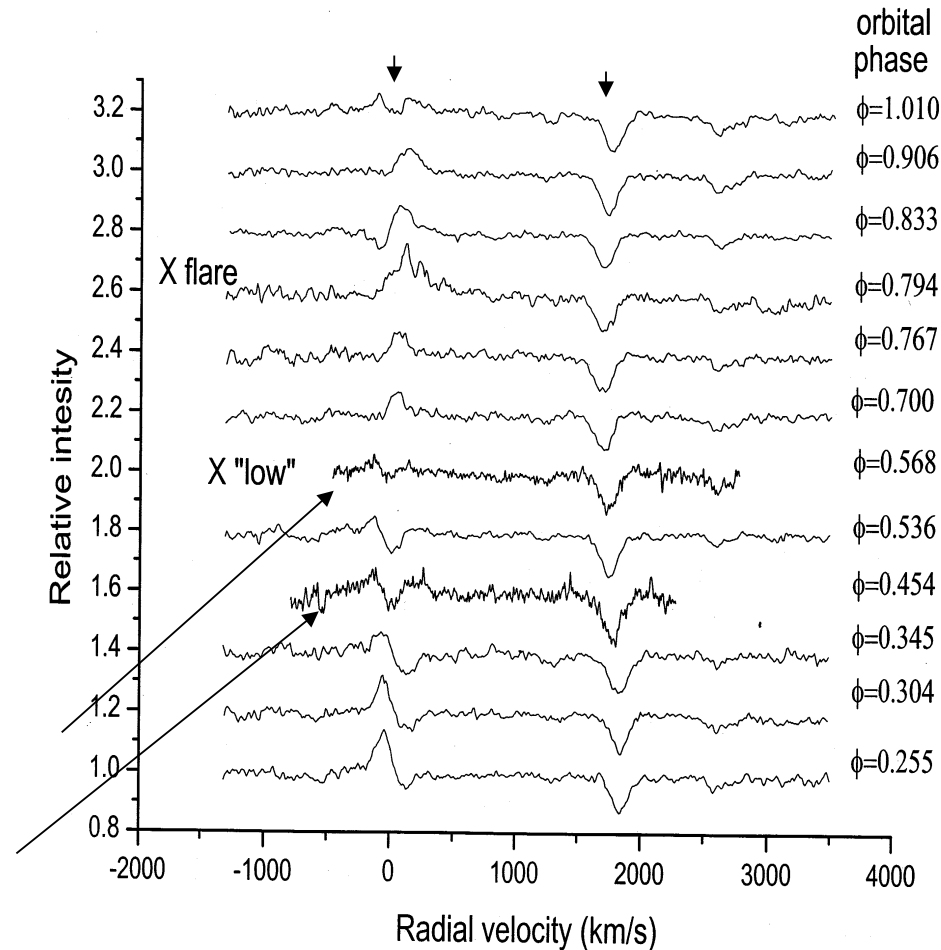


During 33 nights in 2002 - 2004 75 spectra were obtained.

Main spectral features:

- the supergiant absorption lines:
 - H α , HeI, HeII,
 - strong CNO $\lambda 4640\text{\AA}$ blend,
 - multiple lines of heavy elements (C, N, O, Ne, Mg, Si, S, Fe, Zn),
- strong emission components in H α and HeII $\lambda 4686\text{\AA}$ with complex profiles.

Sequences HeII 4686 A и HeI 4713 A profiles against the orbital period phases



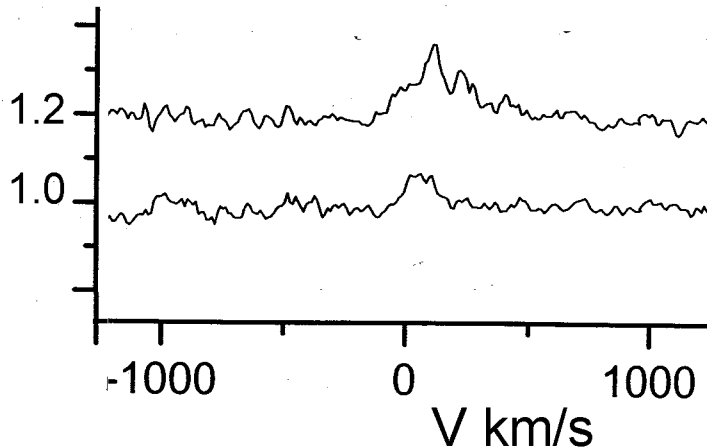
- The Figure shows series of fragments of Cyg X-1 optical spectra against the orbital phase. HeI 4713 A absorption line Doppler shift corresponds to the optical component (supergiant) orbital motion.
- HeII 4686 A line profile variability encloses information on the gas fluxes in the system and on how they are affected by the X-ray radiation variability.

The X-ray Flare of June 13, 2003

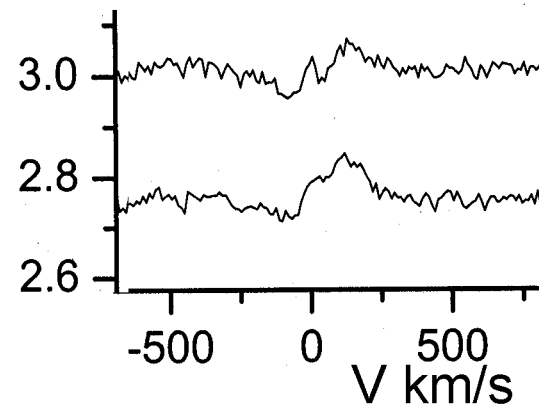
According to RXTE/ASM data, the X-ray flux $F(1.2-12 \text{ keV})$ increased by a factor of 1.7 in 3.7 hours (the time-interval between the expositions)

The line profile variations:

HeII 4686 A



H α



Intensity of HeII 4686A line was increased and H α line was decreased.
So circumstellar gas ionization was increased during the X-ray flare.

Model atmosphere of Cyg X-1 optical star

The main results are reported in:

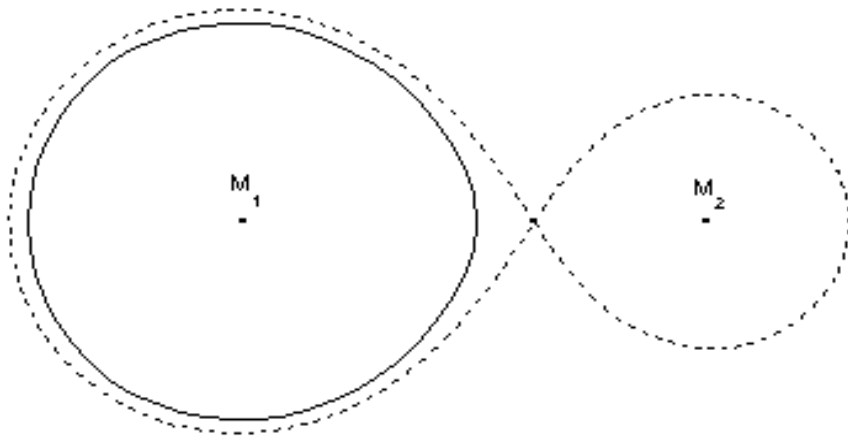
- Karitskaya, E. A.; Agafonov, M. I.; Bochkarev, N. G.; Bondar, A. V.; Galazutdinov, G. A.; Lee, B.-C.; Musaev, F. A.; Sapar, A. A.; Sharova, O. I.; Shimanskii, V. V., 2005, *Astronomical and Astrophysical Transactions*, vol. 24, Issue 5, p.383-389
- Karitskaya E.A., Lyuty V.M., Bochkarev N.G., Shimanskii V. V., Tarasov A. E., Bondar A. V., Galazutdinov G. A., Lee B.-C., Metlova N.V., Long-Term Variations of the Supergiant in the X-Ray Binary Cyg X-1. *Inf. Bull. Var. Stars*, No. 5678, 2006, p. 1-4.
- Karitskaya, E. A.; Shimanskii, V. V.; Sakhbullin, N. A.; Bochkarev, N. G., Peculiarities of the Chemical Composition of the Optical Component of Cyg X-1. In: *Why Galaxies Care about AGB Stars: their Importance as Actors and Probes*. ASP Conf. Series, V. 378, Eds.: F.Kerschbaum, C.Charbonell & R.F.Wing, 2007, p. 123-124.

Cyg X-1 spectra simulation technique

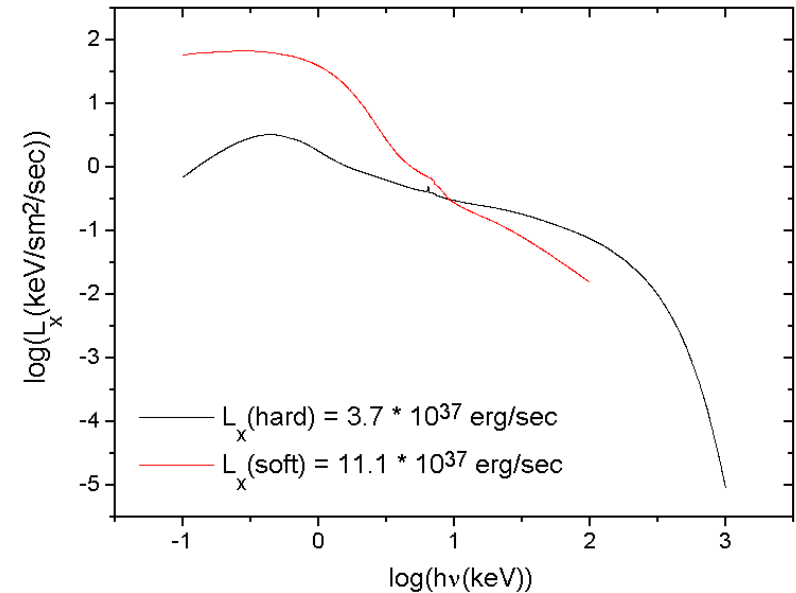
The SPECTR code

(Sakhbullin, Shimanskii, 1997):

- 1) Illuminated atmosphere models with heating and cooling balance (Ivanova et al., 2002);
- 2) Equipotential shape of a star that almost fills its Roche lobe (Shimanskii, 2002);



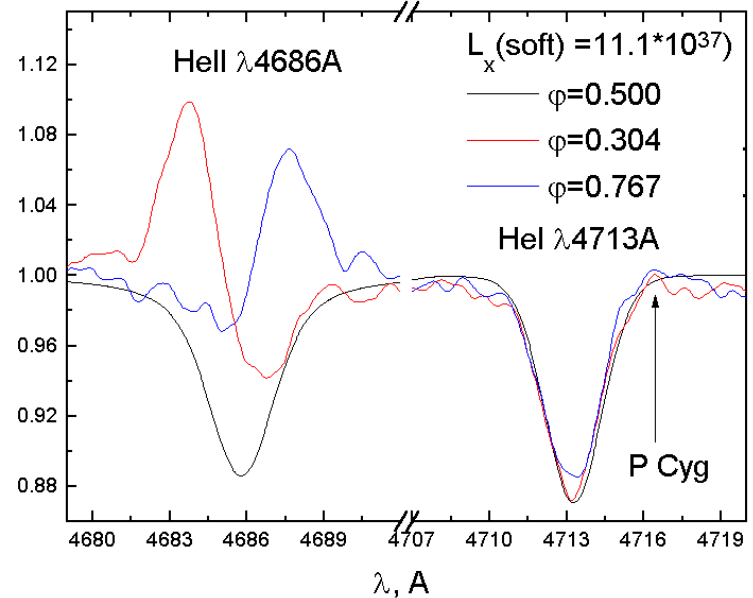
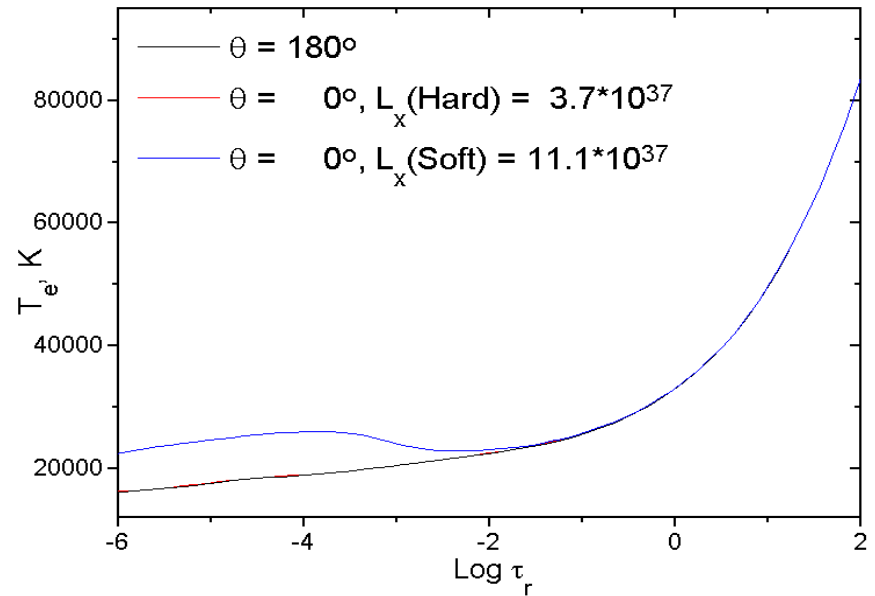
- 3) Two types of outer illumination spectra “soft” - “hard” (A.Zdziarski, M.Gierlinski, (Prog. Theor. Phys. Suppl. No.155, 2004);



- 4) A synthetic spectrum based on 580000 spectral lines (Shimanskii et al., 2003);
- 5) Direct computation of non-LTE effects for H I, He I, Mg II, Si IV with influence of outer illumination (Ivanova et al., 2004).

The obtained results:

- Chromosphere with a temperature excess up to 5000K is formed during the “soft” state of Cyg X-1 only.
- X-ray radiation of any type causes no sensible effect on H I, He I, Mg II, C II, etc. profiles.
- P Cyg emission components in He I $\lambda\lambda$ 4387, 4471, 4713, 4921, 5876 Å profiles;
- Hot wind outflow from the O-star surface at optical depth $\log \tau < -2.0$.



α Cam

Cyg X-1 optical spectra simulation leads to conclusions:

The correct description of H I, He I and other line profiles corresponds to Cyg X-1 O9.7 lab star parameters:

$$T_{\text{eff}} = 30400 \pm 500 \text{ K},$$

$$\log g = 3.31 \pm 0.07,$$

$$[He/H] = 0.02 \pm 0.15$$

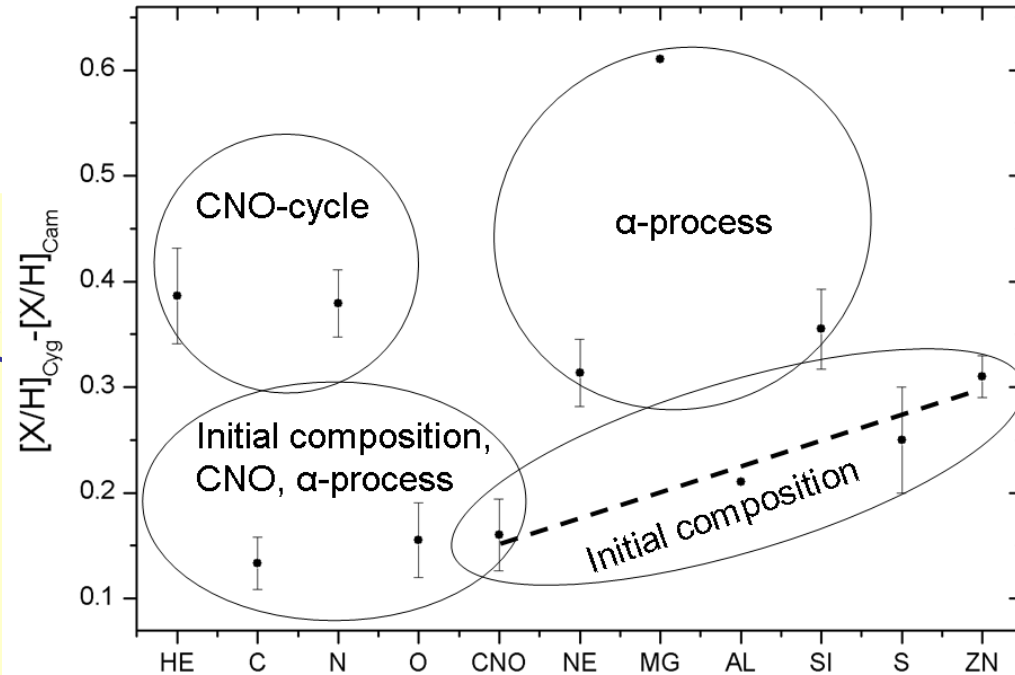
Alpha Cam has very similar characteristics but it is single supergiant O9.5 I.

For α Cam we obtained :

$$T_{\text{eff}} = 30800 \pm 1200 \text{ K},$$

$$\log g = 3.26 \pm 0.10,$$

$$[He/H] = 0.02 \pm 0.15,$$



4 ovals encircle groups of elements subjected to influences:

- 1) CNO cycle of hydrogen fusion,
- 2) alpha--processes of helium fusion,
- 3) both the processes,
- 4) or non of them (initial composition).

Chemical composition conclusions

- Cyg X-1 supergiant atmosphere shows a high (from 0.4 dex to 1.0 dex) excess of He, N, Ne, Mg, Si, that is, the elements affected by CNO– and alpha--processes.

It looks like the mixing of matter ought to be far more effective in that object than in the single star alpha Cam, due, in all probability to tidal interaction and mass exchange with the relativistic component at the preceding and present stages of the system evolution.

- Cyg X-1 star chemical composition is anomalous. It demonstrates an influence of matter transformation as in CNO – cycle and in alpha – processes.
- The detected peculiarities of the chemical composition of Cyg X-1 optical component atmosphere may serve as landmarks for the system evolution recuperation.

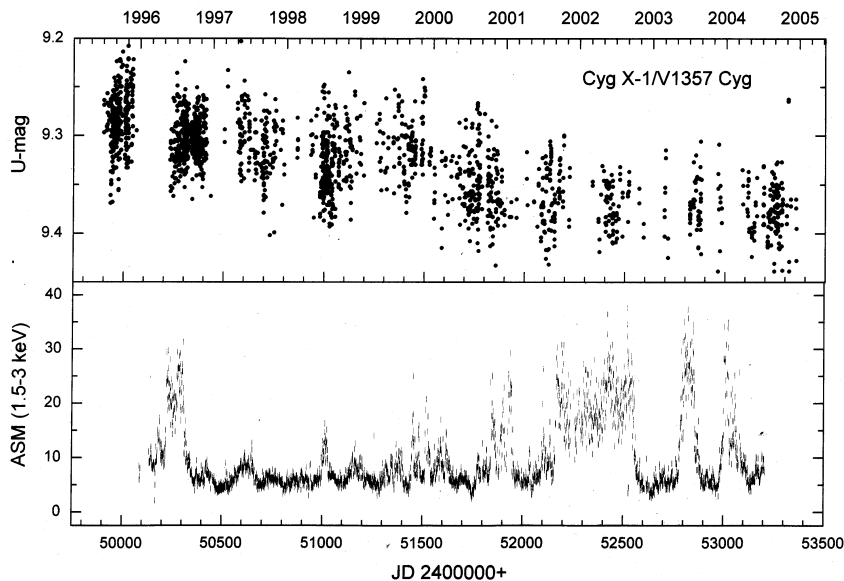
Cyg X-1 system supergiant variability

E.A. Karitskaya, V.M. Lyuty, N.G. Bochkarev, V.V. Shimanskii, et al., 2006a, Long-Term Variations of the Supergiant in the X-Ray Binary Cyg X-1, IBVS, No.5678, pp.1-4.

The 35-year long series of observations performed by V.M.Lyuty at SAI Crimean Laboratory revealed the supergiant light variation on the time-scale tens of years.

Spectral observations at Crimean Astrophysical Observatory in 1997 performed in the Coude focus of the 2.6 m telescope R=35000, $\lambda\lambda$ 4655-4722A June 15-August 16, 1997. 20 spectra were obtained.

Brightness variations in U-band and X-ray activity

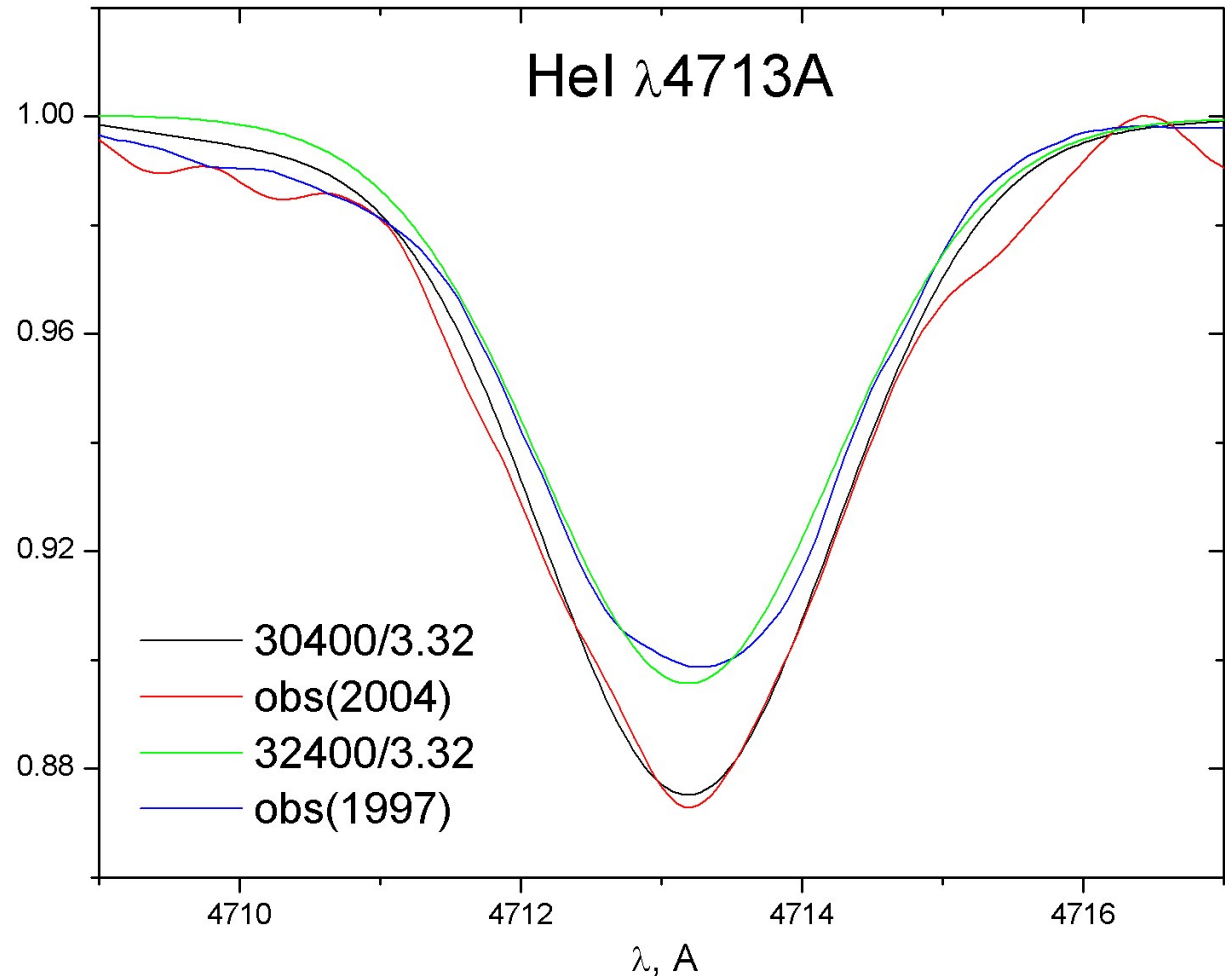


The data were compared with the data obtained at Terskol Observatory and at BOAO (South Korea).

HeI 4713 A line profile: 1997 vs 2004 data

- The 1997 line profile is different – less deep than the 2004 one.
- One example of non-LTE computation for 1997 data is given.

Log $g = 3.32$ is found not to be in agreement with the photometric changes. Therefore combined analysis of photometric and spectral variability has been performed.



Averaged magnitude differences for 2004 vs 1997 according to V.M.Lyuty's photometric observations:

U 0.065 ± 0.003 m,

□ B 0.031 ± 0.003 m,

□ □V 0.029 ± 0.003 m.

Simultaneous matching of non-LTE simulation of the photometric variability and HeI 4713 A line profiles against the observed ones shows that

from 1997 to 2003-2004:

- The star radius has increased by 1-4%,
- The temperature has decreased by 1300-2400 K.

X-ray activity increasing after 1996 is believed to be a result of the supergiant parameter changes.

Imaging Techniques: Cyg X-1 Doppler Tomography

The main results are reported in:

- **Karitskaya, E. A.; Agafonov, M. I.; Bochkarev, N. G.; Bondar, A. V.; Galazutdinov, G. A.; Lee, B.-C.; Musaev, F. A.; Sapar, A. A.; Sharova, O. I.; Shimanskii, V. V.**, 2005, *Astronomical and Astrophysical Transactions*, vol. 24, Issue 5, p.383-389
- **E.A.Karitskaya, M.I.Agafanov, N.G.Bochkarev, A.V.Bondar, G.A.Galazutdinov, B.-C.Lee, F.A.Musaev, O.I.Sharova, V.V.Shimanskii, A.E.Tarasov.** **Results of high-resolution optical spectroscopy investigation of Cyg X-1 = V1357 Cyg**, *Astronomical and Astrophysical Transactions*, v. 26, p. 159-162 (2007)
- **Sharova, O. I.; Agafonov, M. I.; Karitskaya, E. A.; Bochkarev, N. G.; Zharikov, S. V.; Butenko, G. Z.; Bondar, A. V.**, Three-Dimensional Doppler Tomography of the X-ray Binary Cyg X-1. In: *Variable Stars, the Galactic Halo and Galaxy Formation*. Eds. Ch.Sterken, N.Samus, L.Sabodos, Moscow: SAI MSU, 2010, p. 212.

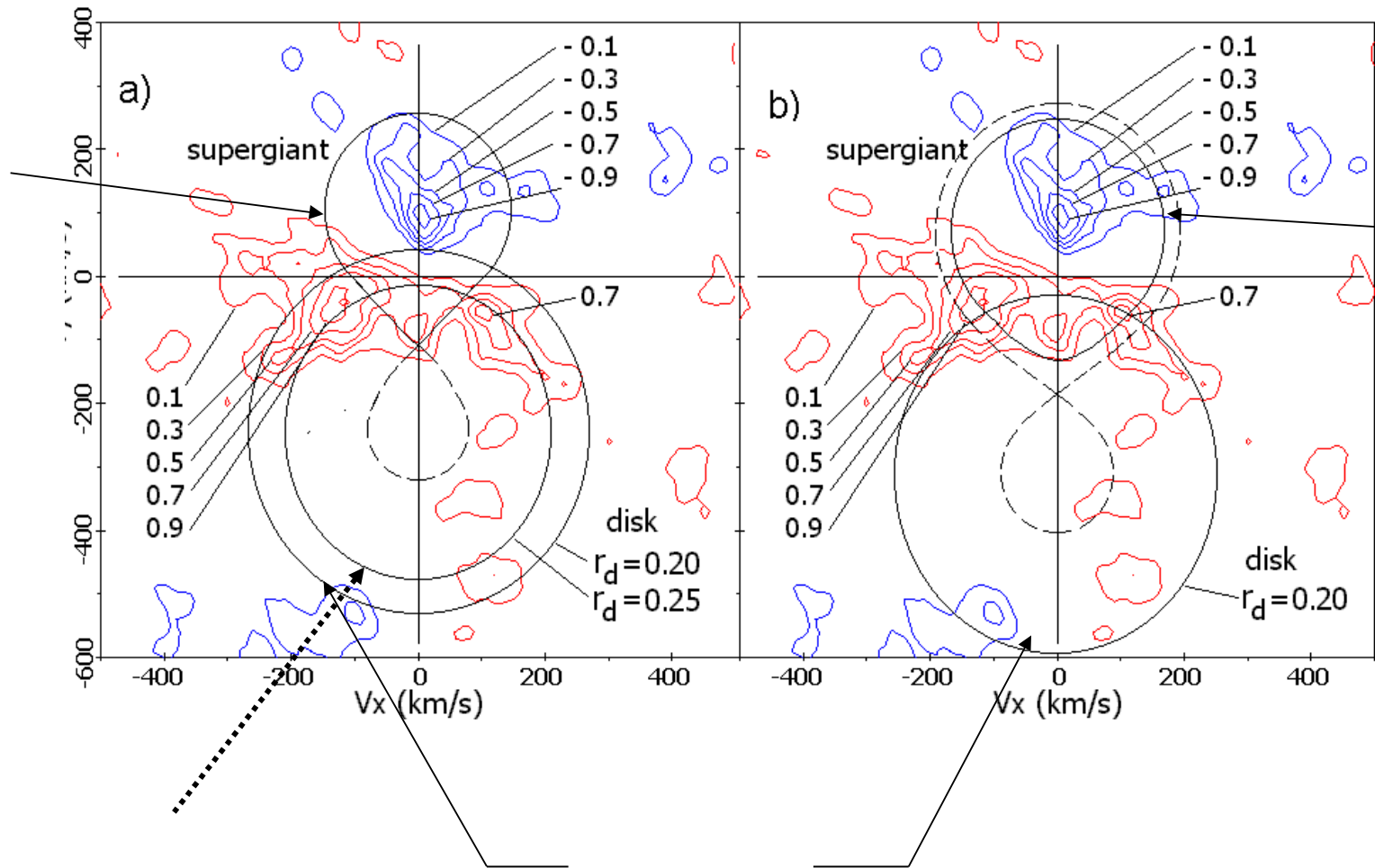
A tomogram (tomography map), i.e., spectral intensity distribution in the velocity space constructed over spectral line profiles.

A technique based on the radioastronomical approach (RA) was used (Agafonov, 2004, *Astronomische Nachrichten*, v.325, No.3, p.259-262 & p.263).

The results of 3D tomography reconstruction of Cyg X-1 see poster presented on this meeting :

Sharova, O. I.; Agafonov, M. I.; Karitskaya, E. A.; Bochkarev, N. G. et al.

Cyg X-1 2D tomogram in He II 4686 A line during “soft” state of the X-ray spectrum (June 2003, Peak Terskol)



Comparison with the system parameters

Comparison with the system parameters

Cyg X-1 tomogram in He II 4686 A line during “hard” state of the X-ray spectrum (June 2004, Peak Terskol)

The blue isolines (absorption component of the line) in upper part of the Figure correspond to the supergiant region opposite to BH and should be inside the Roche lobe. It yields the **upper limit**:

$$q = M_x/M_o = 1/3.$$

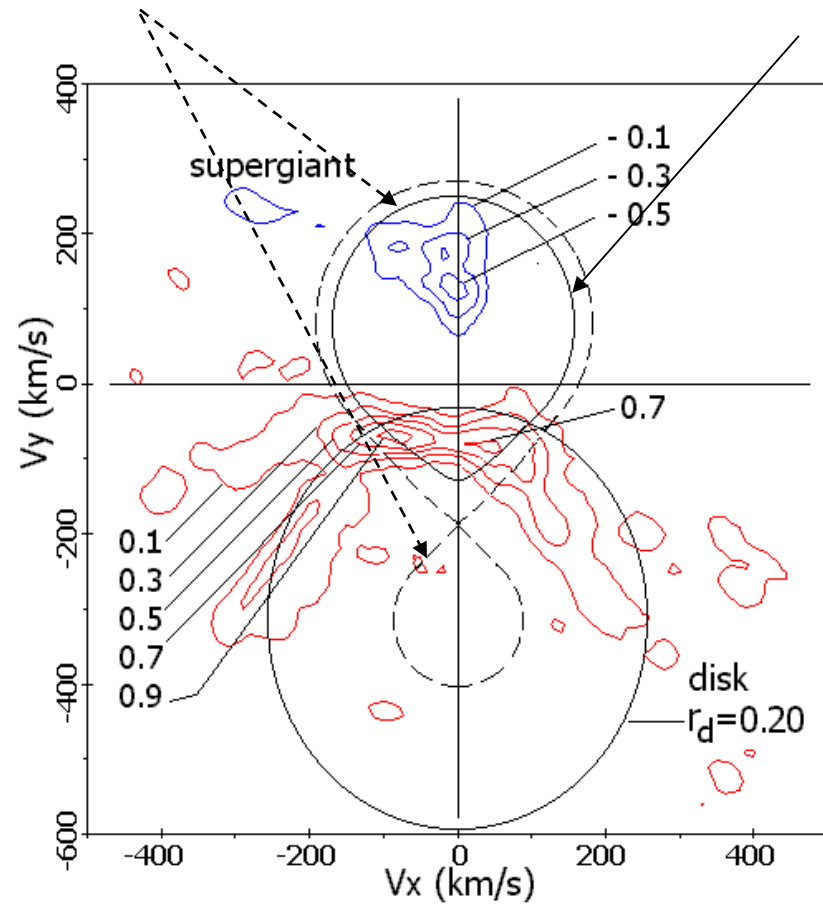
On the other hand, the star must almost fill its Roche lobe, which yields the **lower limit**:

$$q = M_x/M_o = 1/4.$$

The ovals correspond to the disk radii $r_d = 0.2$ and 0.25 in the units of the distance between the components.

The emission parts of He II 4686A line (the red isolines) may be generated in:

- the outer parts of the accretion disk heated by the supergiant;
- in the “hot line” (Kuznetsov et al., 2001);
- and/or the hot stream (focused stellar wind).



Doppler Tomography in 2D and 3D of the X-ray Binary Cyg X-1 for June, 2007

**Sharova O.I. 1), Agafonov M.I. 1), Karitskaya E.A. 2),
Bochkarev N.G. 3), Zharikov S.V. 4), Butenko G.Z. 5),
Bondar' A.V. 5)**

- on the base of the spectral data for the line HeII 4686 A obtained with 2-m telescope of the Peak Terskol Observatory (Russia) and 2.1-m telescope of the Mexican National Astronomical Observatory in June, 2007.
- Information about gas motions in the out of the orbital plane by using of all the three velocity components V_x, V_y, V_z were estimated for the first time.
- The **features with high intensity in emission** (1) the **emission of the accretion structure** that is located around the compact object but on the side next to the donor-star; 2) the **elongated feature of the stream** from L1 point; 3) the emission of the **stream – accretion structure interaction**) and in **absorption** (the compact area of the **supergiant**)

An interesting emission feature also associated with the donor-star is in the slices of the low row by the values of $V_z = -200, -280, -360$ km/s. Its intensity is equal to about ~20-30% from the maximum intensity of 3D tomogram. That is probably a stream from the donor-star that is visible in emission and that flows almost perpendicularly to the orbital plane

Abstract

The 2D and 3D Doppler tomograms of the X-ray binary system Cyg X-1 (V1357 Cyg) were reconstructed on the base of the spectral data for the line HeII 4686 Å obtained with 2-m telescope of the Peak Terskol Observatory (Russia) and 2.1-m telescope of the Mexican National Astronomical Observatory in June, 2007. Information about gas motions in the out of the orbital plane by using of all the three velocity components V_x, V_y, V_z were estimated for the first time. The realization of the 3D Doppler tomography became possible due to the developed Radioastronomical Approach to reconstruction in the few projection tomography. The tomograms reconstruction was carried out for the system inclination angle of 45° . The equal resolution ($50 \times 50 \times 50$ km/s) is realized in this case as in the orbital plane (V_x, V_y) so in the perpendicular direction V_z . The checkout tomograms were realized also for the inclination angle of 40° because of the angle uncertainty. Two versions of the results showed no qualitative discrepancy. Structure details revealed by the 3D Doppler tomogram were analyzed.

The 2D tomograms for June 2007 are similar to those reconstructed earlier (for 1997, 2003 and 2004). They give evidences for the emission component of the HeII 4686 Å line being generated mainly in the outer parts of the Cyg X-1 accretion structure closest to the donor star (O-supergiant). The absorption component is formed in the atmosphere of the supergiant. The comparison using the Chi-square method of the observed line profiles with the computed ones (recovered from the reconstructed tomograms) shows a good quality of reconstruction.

Spectropolarimetric observations. Magnetic field discovery in Cyg X-1

The main results are reported in:

- E.A.Karitskaya, N.G.Bochkarev, S.Hubrig, Yu.N.Gnedin, M.A.Pogodin, R.V.Yudin, M.I.Agafonov, O.I.Sharova Magnetic Field in X-ray Binary Cyg X-1, 2009, arXiv: astro-ph 0908.2719
- E.A.Karitskaya, N.G.Bochkarev, S.Hubrig, Yu.N.Gnedin, M.A.Pogodin, R.V.Yudin, M.I.Agafonov, O.I.Sharova, 2010, The first discovery of a variable magnetic field in X-ray binary Cyg X-1 = V1357 Cyg, IBVS, No. 5950, 1
- Karitskaya, Eugenia A.; Bochkarev, N.G.; Hubrig, S.; Gnedin, Yu.N.; Pogodin, M.A.; Yudin, R.V.; Agafonov, M.I.; Sharova, O.I., The magnetic field in the X-ray binary Cyg X-1. In: Cosmic Magnetic Fields: from Planets to Stars and Galaxies, Eds. K. G. Strassmeier, A.G. Kosovichev, J. Beckman, Cambridge Univ. Press,. IAU Symp. 259, 2009, p. 137-138.

Some Developments of the Weak Stellar Magnetic Field Determination Method

on

the Example of

Cyg X-1

N.G.Bochkarev

Sternberg Astron. Inst., Moscow, Russia

E.A.Karitskaya

Inst. of Astron. RAS, Moscow, Russia

Abstract

Some developments of measurements of the weak stellar magnetic fields by the least square technique applied to spectropolarimetric data are proposed and used for the X-ray binary Cyg X-1=HDE 226868 (the optical counterpart is an O9.7 supergiant). The $V//$ circular polarization spectra obtained during our spectropolarimetric FORS1 VLT observations have variable sloped continuum components not belonging to the object. It is shown that such components should be removed, otherwise these false sloped continua yield biased results. For HDE226868 the mean longitudinal magnetic field bias $\Delta\langle B_z \rangle$ varies from 20 G to 100 G, which is comparable to its value. The slopes of I -spectra have smaller influence on $\langle B_z \rangle$ result but they should be subtracted too. We also consider the initial I - and $V//$ -spectra cleaning, effects from the deviating points, and their influence on the results of $\langle B_z \rangle$ measurements.

By using these developments we could detect magnetic field in Cyg X-1. That is the first successful measurement of magnetic field in a binary with a black hole. The value of the mean longitudinal magnetic field in optical component (9.7 lab supergiant) changes regularly with the orbital phase reaching its maximum of 130 G ($\sigma \approx 20$ G).

The measurements based on Zeeman effect were carried through over all the observed supergiant photosphere absorption spectral lines. Similar measurements over the emission line He II 4686 Å yielded a value of several hundreds Gauss with a smaller significance level.

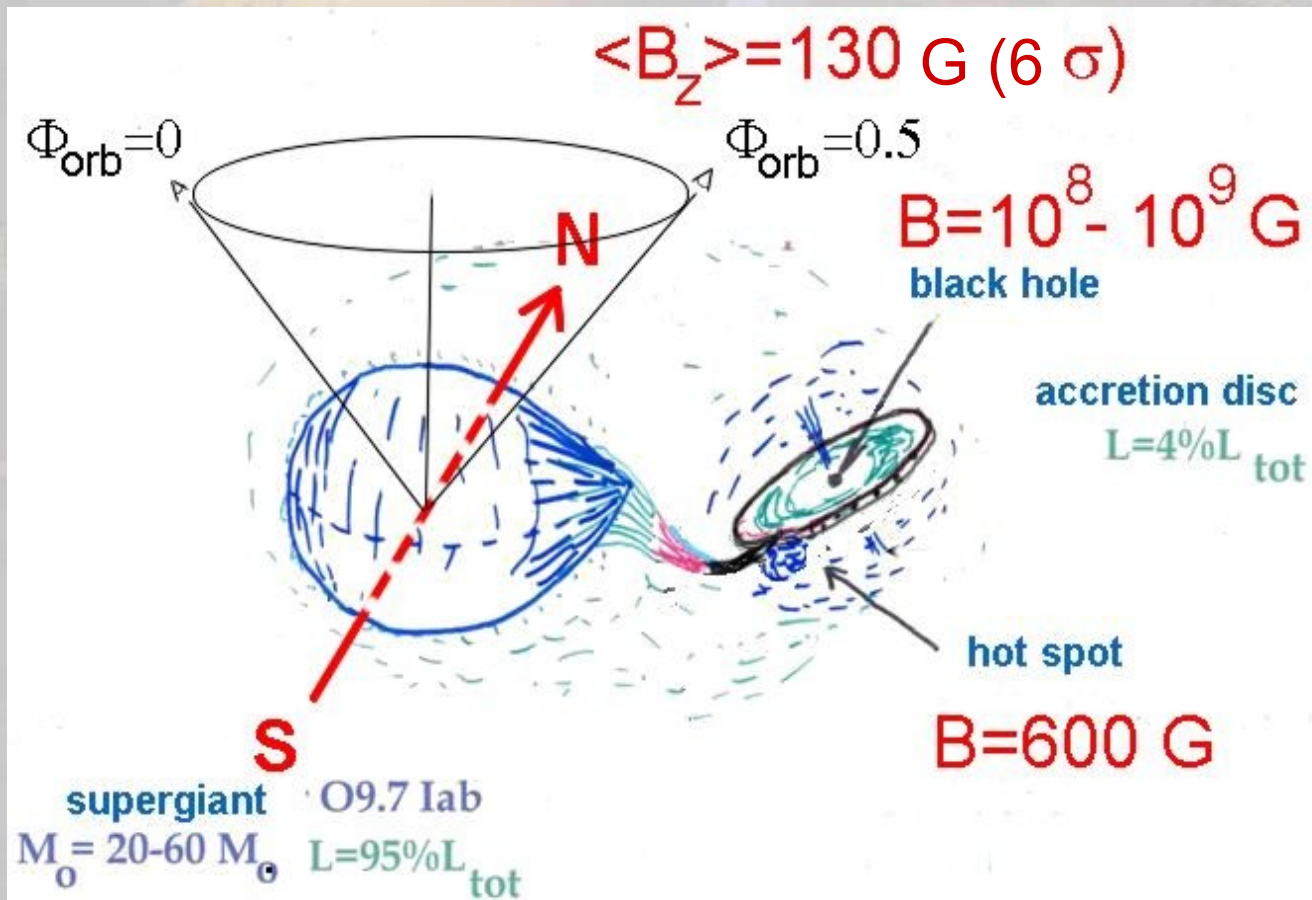
Our VLT FORS1 spectropolarimetric 2007 -2008 observations permitted us to reveal the magnetic field of ~ 100 G on the supergiant in Cyg X-1 and to suspect the magnetic field of ~ 600 G on the accretion structure outer limit.

It is the pioneer measurement in black hole systems.

The field is enough for X-ray flickering.

For details see poster by Bochkarev N.G. and Karitskaya E.A.

It is the first observational confirmation of magnetic disc accretion on black hole (including AGNs).



Sources of wavelength-dependant circular polarization of optical continuum

- In contrast to previously studied stars (mainly A and late B types), luminous O-stars have usually significant interstellar / circumstellar linear (up to $\sim 10\%$) and weak circular ($< 0.05\%$) polarization in optical continuum.
 - Any spectropolarimeter has cross-talk between linear and circular polarization within analysing equipment. It creates a false circularly polarized wavelength-dependant continual component of radiation for stars with linear polarization.
- As a result, more and more often targets for magnetic field measuring has spectra of Stokes parameter V (measuring circular polarization) and ratio V/I (I is Stokes parameter for total intensity) containing wavelength-dependant continual components $C_V(\lambda)$ and $C_{V/I}(\lambda)$, λ is wavelength.

Cyg X-1 = HDE 226868 observations

- Very Large Telescope (VLT) 8.2 m (Mount Paranal, Chile);
- Spectropolarimetry with FORS1 spectrograph;
- Resolution $R=4000$;
- Range 3680-5129 Å;
- S/N = 1500 – 3500 (for I);
- since June 18 over July 9, 2007

- since July 14 over July 30, 2008 (Cyg X-1 in X-ray hard state)
13 nights of 1-hour observations

→ **13 spectra of intensity I and circular polarization V** were obtained.



The method of the magnetic field measurement

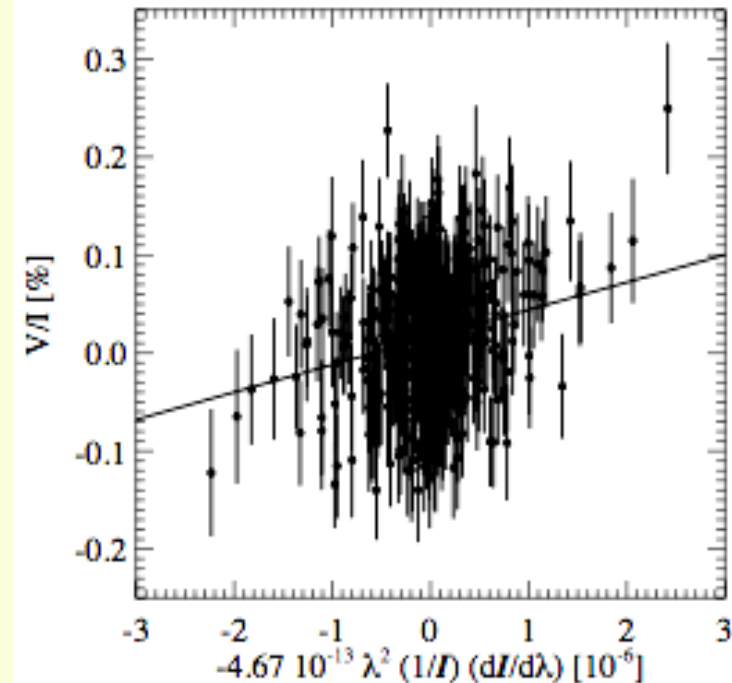
Mean longitudinal magnetic field $\langle B_z \rangle$ was determined by statistical processing of spectra of circular polarization $V(\lambda)$ and intensity $I(\lambda)$, using equation (e.g. Landstreet 1982):

$$\frac{V}{I} = -\frac{g_{\text{eff}} e \lambda^2}{4\pi m_e c^2} \frac{1}{I} \frac{dI}{d\lambda} \langle B_z \rangle$$

where g_{eff} is the effective Lande factor,

$$C_z = e/(4 \pi m_e c^2) = 4.67 \cdot 10^{-13} \text{ \AA}^{-1} \text{ G}^{-1}.$$

Least squares method (LSM) used for $\langle B_z \rangle$ calculation (for details see, e.g., Bagnulo et al. 2002, 2006; Hubrig et al. 2004).

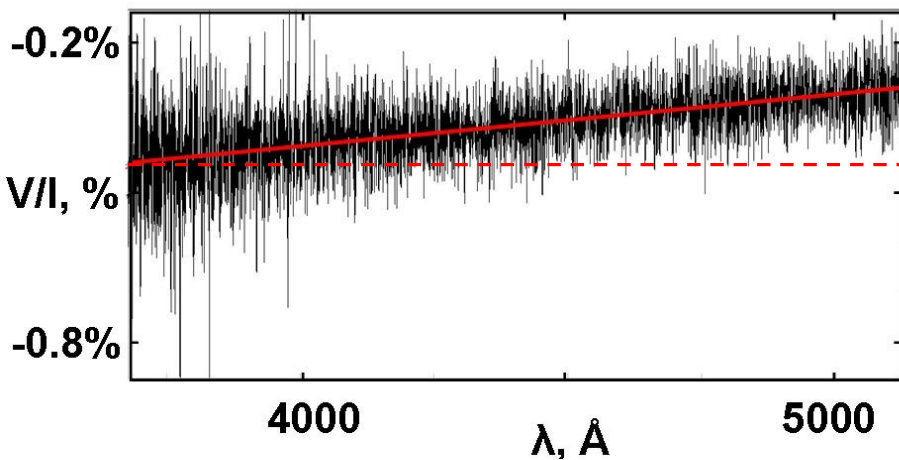


Sources of noise of $\langle B \rangle$ measurements, which should be removed from I - and V/I -spectra

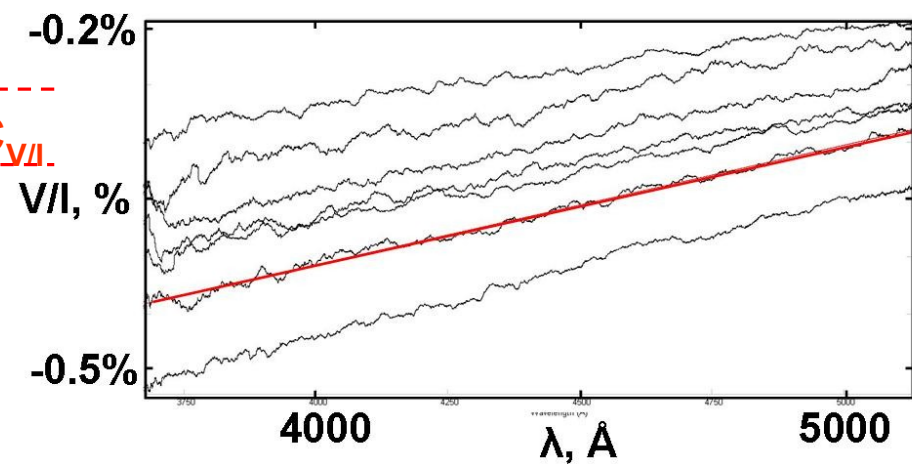
- 1) **interstellar lines and narrow diffuse interstellar bands** (DIBs);
- 2) **defects** (including residual cosmic ray tracks that remained after the standard observation processing);
- 3) **He II 4686A line** with complicated profile including the accretion-structure emission component (the second emission line $H\alpha$ is situated outside the spectral range of our VLT observations);
- 4) emission components of **lines with P Cyg effect**.
- In addition **we removed some λ intervals containing no observed lines besides noise.**
- **We found no pollution by telluric lines in our spectra.**

Observed V/I-spectra slopes (V/I-trends)

Slope value $S = dC_{V/I}/d\lambda \sim 10^{-6}\text{\AA}^{-1}$ is irregularly varied from night to night.



V/I-spectrum Cyg X-1 for a night (black line) and its linear regression (red slop line)



All V/I-spectra of 2008 smoothed by 50 \AA -width Gauss filter (black lines) and the linear regression shown in the left box (red line)

The most probable reason of the V/I-spectra slopes is a **cross-talk** between linear and circular polarization within analysing equipment.

Influences of the V/I-trends on results of $\langle B_z \rangle$ measurements

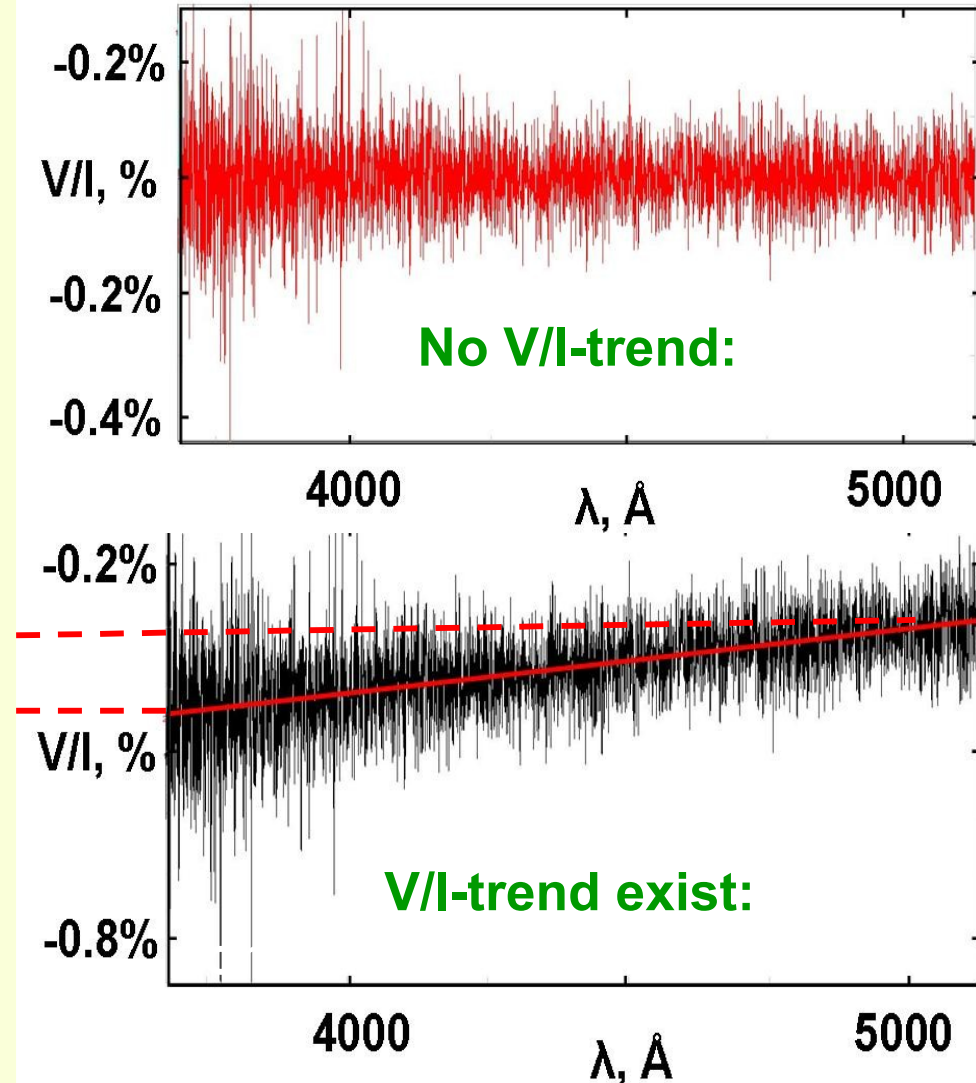
Application of a least squares method (LSM) to data with **non-removed V/I trend results in distorted or even false $\langle B_z \rangle$ value and its significance.**

There are at least 2 reasons for it:

- 1) **Strong violation of residuals Gauss statistic;**
- 2) **Appearance of false $\langle B_z \rangle$ component.**

False $\langle B_z \rangle$ component is

$$\sim (\Delta\lambda_D / \lambda)^2 * dC_{V/I} / d\lambda$$



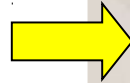
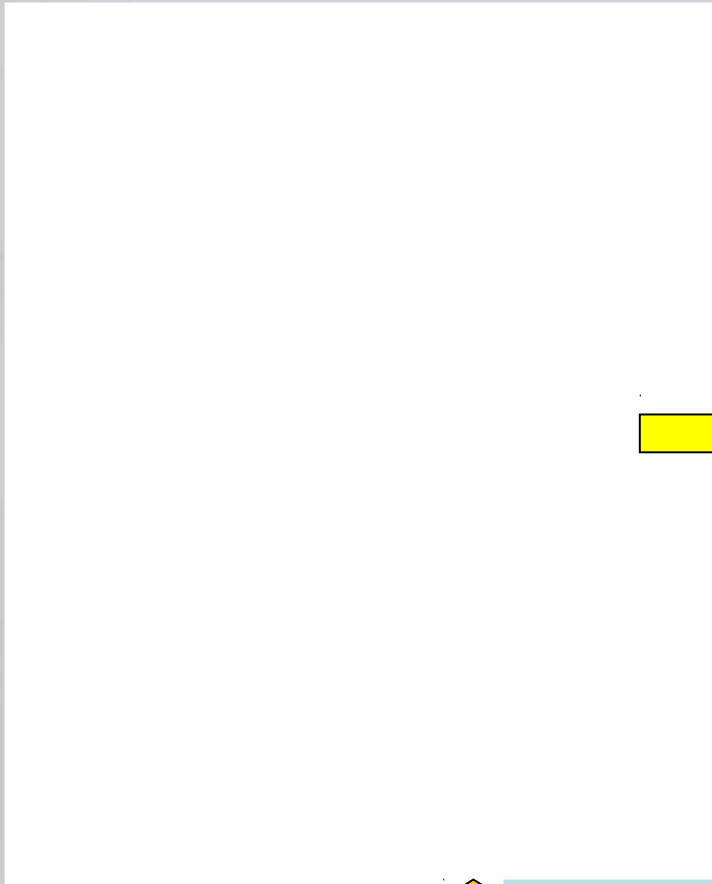
Corrections of Cyg X-1 optical component $\langle B_z \rangle$ produced by the V/I-continuum slope removing

- For our Cyg X-1 FORS1 observations **false $\langle B_z \rangle$ from single spectral line** and sloped V/I continuum without Zeeman S-waves **is several Gauss.**
- To avoid any influence of the V/I-continuum slope on our $\langle B_z \rangle$ measurements, **we subtracted linear trends from V/I spectra.**
- For our Cyg X-1 VLT observations **non-removed V/I-spectra slopes create $\langle B_z \rangle$ shifts from 20 to 84 G.**
- All $\langle B_z \rangle$ corrections are negative.

Influence of I-spectra slopes on $\langle B_z \rangle$

- We normalized I-spectra by pseudo-continuum.
- Wavelength dependence of I-continuum $I(\lambda)$ is produced by:
 - the source energy distribution,
 - interstellar reddening,
 - broad diffuse interstellar bands (DIBs),
 - atmospheric extinction,
 - used equipment detector sensitivity.
- I-spectrum slopes reach $|d(\log(I(\lambda)))/d(\log(\lambda))| \sim 20$.
- The slope removing gives $\langle B_z \rangle$ correction up to ~ 20 G.
- It is usually less than the statistical errors $\sigma(\langle B_z \rangle) \sim 20 - 30$ G.

Results of $\langle B_z \rangle$ measurements of Cyg X-1 optical component



About 6 sigma!



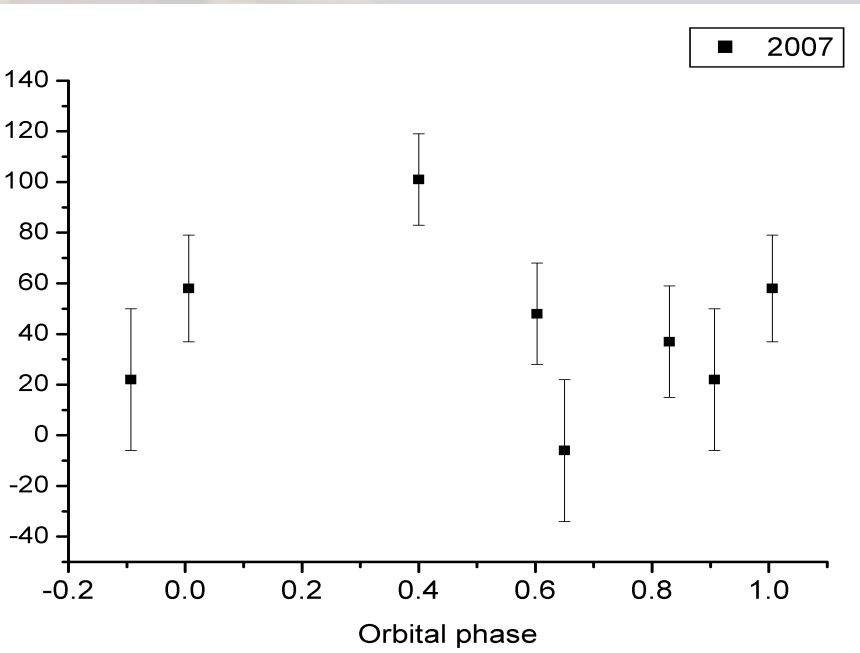
About 6 sigma!

Tests:

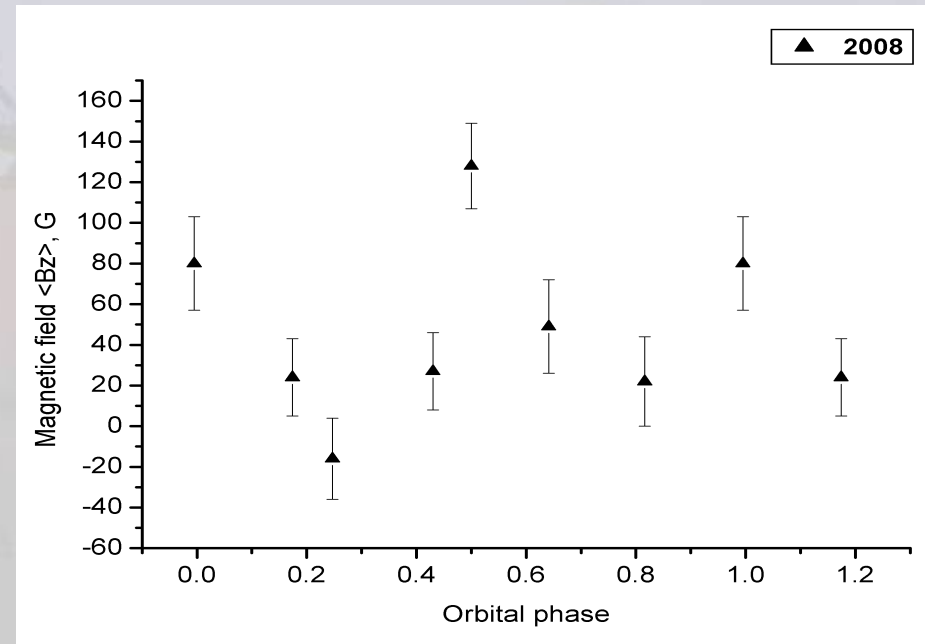
- 1) Each spectrum was divided in two halves at mid-wavelength; $\langle B_z \rangle$, determined over each half separately were coincided within error.
- 2) “Zeeman S-waves” for the strongest lines (e.g. Hel 4026 A) were found.
- 3) Deviations have Gauss statistic up to >3.5 sigma. It is an accuracy estimation control.

Results of $\langle B_z \rangle$ measurements of Cyg X-1 optical component

2007



2008

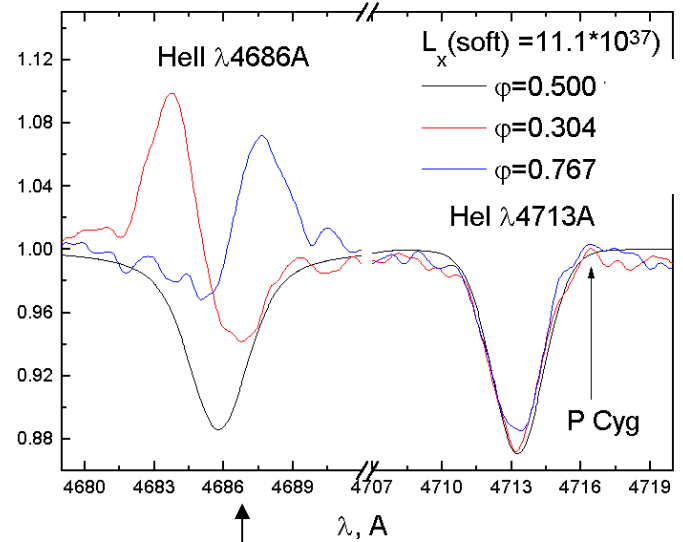


It is very possible that the orbital magnetic curve is varying with time

Analysis of He II 4686 A spectral line

emission (accretion structure)

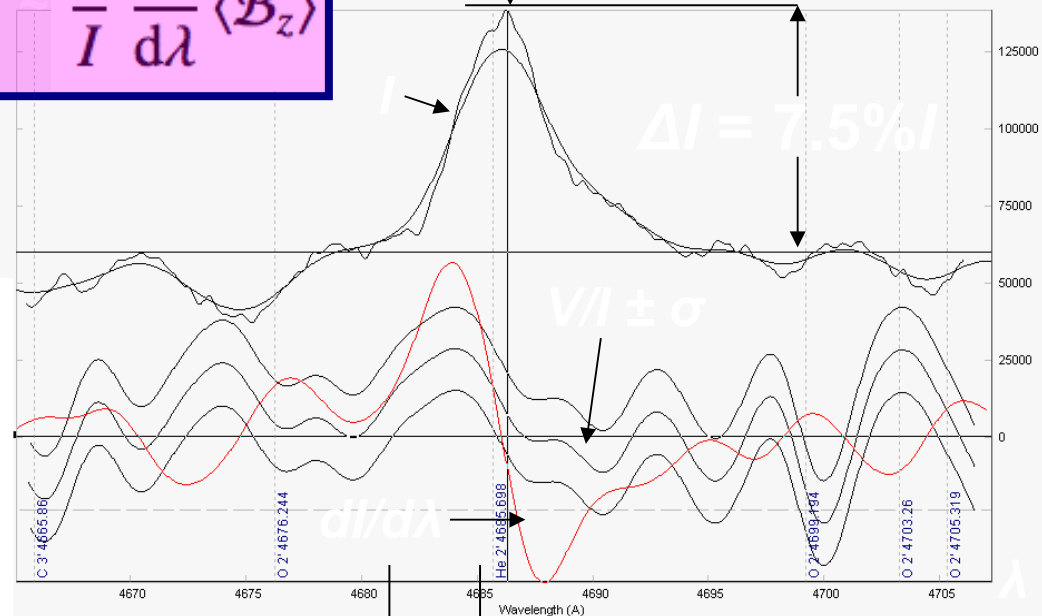
It was omitted from the earlier analysis!



4 sigma

$$\frac{V}{I} = \frac{1}{I} \frac{dI}{d\lambda} \langle B_z \rangle$$

He II 4686 A



<Bz> = -730 +/- 170 G

<Bz> = +420 +/- 105 G

<Bz> reality is confirmed:

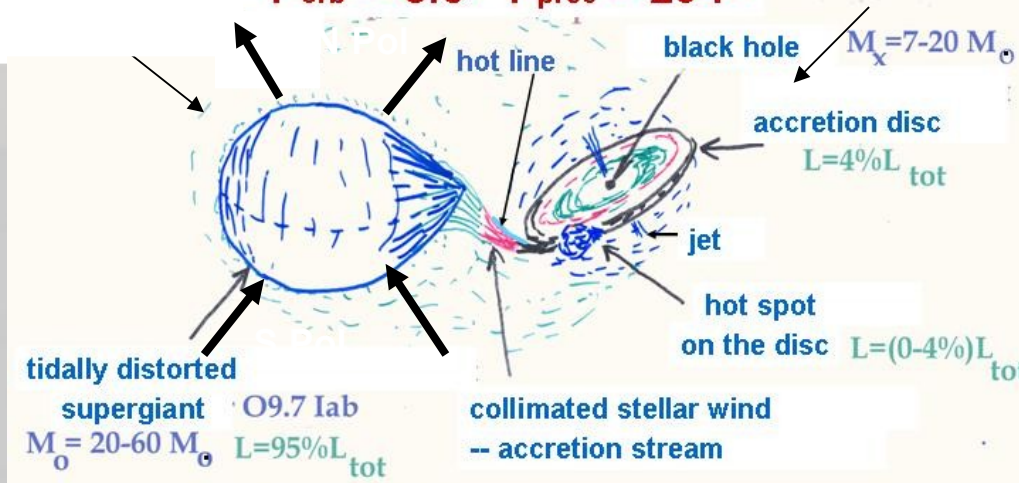
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3A

Cyg X-1 Magnetic Field

Scheme of X-Ray Binary Cyg X-1

$P_{\text{orb}} = 5.6^{\text{d}}$ $P_{\text{prec}} = 294^{\text{d}}$ Obs $\phi = 0.5$

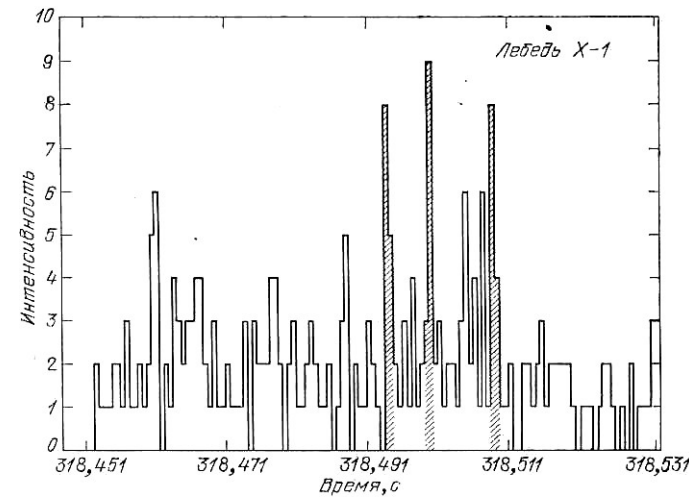


Distance $d = 2-2.5$ kpc (>1.8 kpc)

\rightarrow at $3 R_g$ $B \sim 10^9$ G.

$B(3 R_g) \sim (2-3) 10^8$ G

Can magnetic field of the disc inner region account for Cyg X-1 X-ray flickering?



10^{37} erg/s

$(0.5-1)10^{37}$ erg/s

magnetic energy can account for the flickering.

