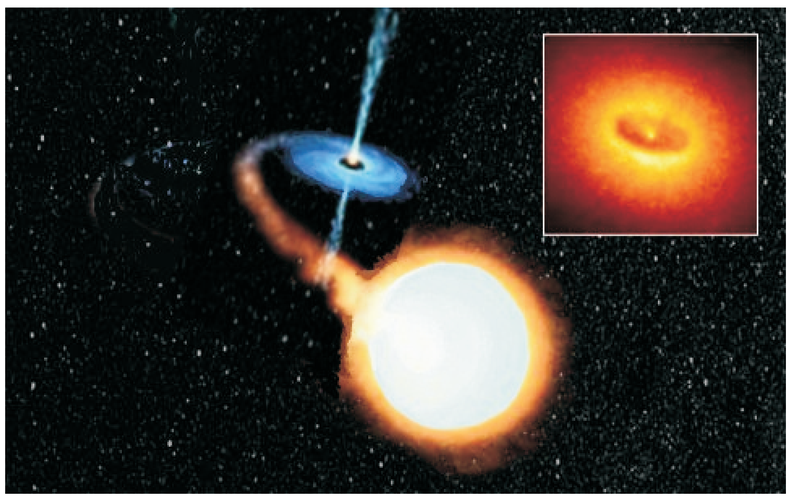

Multi-Technique Study of the X-Ray Binary Cyg X-1

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ABSTRACT. **Short review of our 36-year Cyg X-1 studying by using multi-technique methods and based on our optical photometric, high-resolution spectral and spectropolarimetric observations.**
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 instandard 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_{eff}= 30400+/-500 K, logg = 3.31+/-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 α-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 - 2400 K.
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 syste model and receive better information on the gas flowing. The hard limits on Cyg X-1 component mass ratio were obtained by such manner: $1/4<M_x/M_o<1/3$.
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.

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 UBVR 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

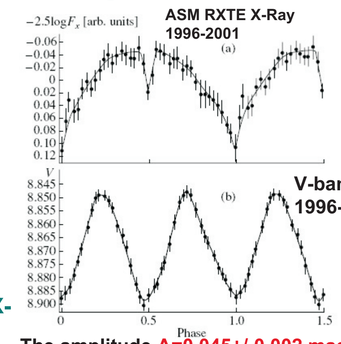
- 1. The shape variations of X-ray orbital light curve.
- 2. Unusual optical deep fading in November,1996.
- 3. Several-day-long optical flares coincided with X-ray dips.

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



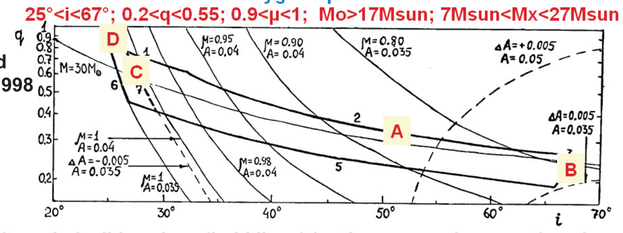
The amplitude A=0.045+/-0.002 mag
The difference minima depth
△A=0.003+/-0.002 mag

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 > 2kpc, Teff < 35000 K
the admissible values of Cyg X-1 parameters were obtained:
25°<i<67°; 0.2<q<0.55; 0.9<μ<1; Mo>17Msun; 7Msun<Mx<27Msun



Our admissible values (bold lines) for the mass ratio *q* as a function of the orbital inclination angle *i* *vs* 4 best models A-D from J.A.Orosz et al. Astro-ph, 1106.3689, 18 June 2011

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~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 ~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 measurment) obtained d=1.75-1.98 kpc and velocity ~21 km/s.

In the case of short scale of distances in Galaxy (RG =7.5 kpc) the distance to CygOB3 association d ~1.8 kpc (Melnik, Dambis, 2009, MNRAS, 400, 518)- Cyg X-1 was born in CygOB3 not more than 8 Myr ago.

The spectroscopy of Cyg X-1 in 2002-2004

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

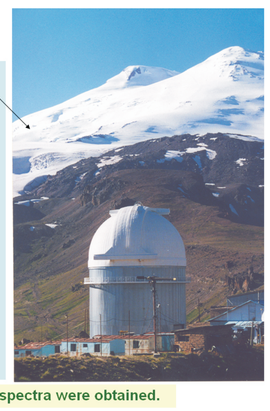
- E.A.Karitskaya, Kinematika i Fizika Nebesnykh Tel, Suppl. No.4 230-233 (2003).

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 Å;
  -- Cassegrain Focus: R = 13000, 3800 – 7600 Å.
- BOAO Observatory (South Korea): 1.84 m telescope fiber echelle-spectrograph: R = 44000 & 30000, 3800 – 10000 A.

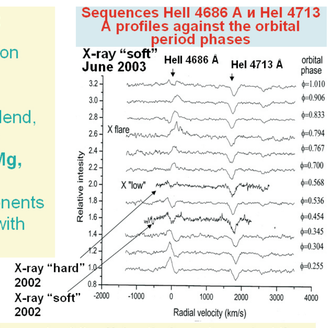


During 33 nights in 2002 - 2004 75 spectra were obtained.

Main spectral features:

- the supergiant absorption lines:
  -- **HI, HeI, HeII,**
  -- strong **CNO λ4640Å** blend,
  -- multiple lines of heavy elements (**C, N, O, Ne, Mg, Si, S, Fe, Zn**),
- strong emission components in **Hα** and **HeII λ4686Å** with complex profiles.

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

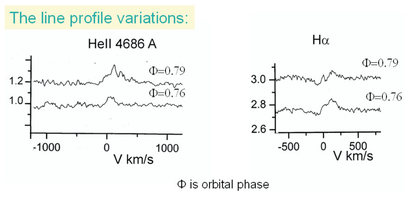


- **The Figure shows series of fragments of Cyg X-1 optical spectra against the orbital phase. HeI 4713 A absorption line Doppler shift corresponds to the optical component (supergiant) orbital motion.**
- **HeII 4686 A line profile variability encloses information on the gas fluxes in the system and 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 keV) increased by a factor of 1.7 in 3.7 hours (the time-interval between the expositions)

The line profile variations:



Φ is orbital phase

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

Model atmosphere of Cyg X-1 optical star

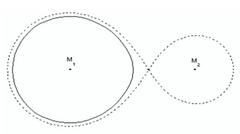
The main results are reported in:

- 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.; Sakhibullin, 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.

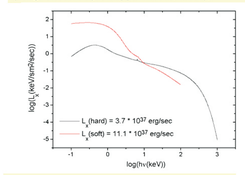
Cyg X-1 spectra simulation technique

The SPECTR code (Sakhibullin, 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);



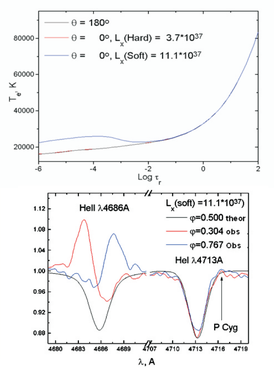
3) Two types of outer illumination spectra "soft" - "hard" (A.Zdziarski, M.Gierlinski, (Prog. Theor. Phys. Suppl. No.155, 2004):



4) A synthetic spectrum based on 580000 spectral lines (Shimanskii et al., 2003);
5) Direct computation of non-LTE effects for HI, HeI, MgII, SiIV 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 HI, HeI, MgII, CII, etc. profiles.
- P Cyg emission components in HeI λλ4387, 4471, 4713, 4921, 5876 Å profiles;
- Hot wind outflow from the O-star surface at optical depth log τ < -2.0.

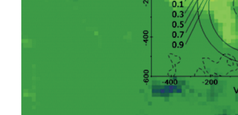


Cyg X-1 system supergiant variability

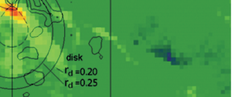
E.A. Karitskaya, V.M. Lyuty, N.G. Bochkarev, V.V. Shimanskii, et al., 2006a, Long-Term Variations of the Supergiant in the X-Ray Binary Cyg X-1, IBVS, No.5678, pp.1-4.

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.

Brightness variations in U-band and X-ray activity



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



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.

Cyg X-1 main characteristics and chemical composition. Comparison with *α* Cam

Cyg X-1 optical spectra simulation leads to conclusions:

The correct description of HI, HeI and other line profiles corresponds to Cyg X-1 O9.7 lab star parameters:
T_{eff} = 30400 +/- 500 K,
log g =3.31 +/- 0.07,
[He/H] = 0.43 +/- 0.06,

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

For *α* Cam we obtained :
Teff = 30800 +/- 1200K,
log *g* = 3.26 +/- 0.10,
[*He/H*] = 0.02 +/- 0.15,

Differences between the element to hydrogen abundance ratio logarithms in HDE 226868 and alpha Cam photospheres.
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).

Imaging Techniques: Cyg X-1 Doppler Tomography

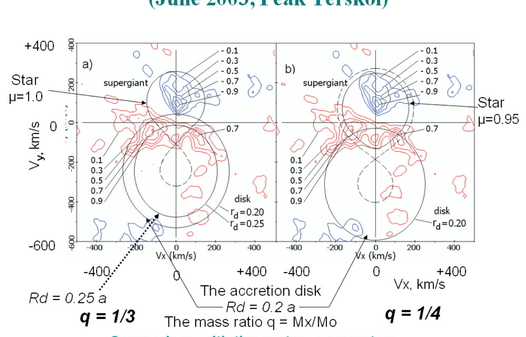
The main results are reported in:

- 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.
DOPPLER TOMOGRAPHY IN 2D AND 3D OF THE X-RAY BINARY CYG X-1 FOR JUNE, 2007

2D tomogram on the base of VLT spectra, June 2007

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

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:**

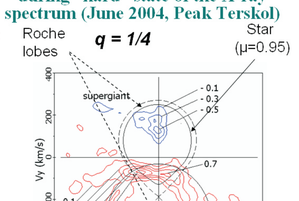
q = Mx/Mo=1/3.

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

q = Mx/Mo=1/4.

The ovals correspond the the disk radii r_d = 0.2 and 0.25 in the units of the distance between the components. The emission parts of HeII 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).

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



Spectropolarimetrical 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.

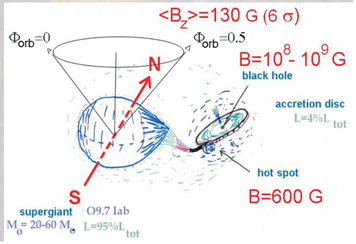
Our VLT FORS1 spectropolarimetric 2007 -2008 observations permitted us to reveal the magnetic field of ~100 G on the supergiant in Cyg X-1 and to suspect the magnetic field of ~600 G on the accretion structure outer limit.

It is the pioneer measurement in black hole systems.

The energy of magnetic field is enough for X-ray flickering.

For details see poster Bochkarev N.G. and Karitskaya E.A. **SOME DEVELOPMENTS OF THE WEAK STELLAR MAGNETIC FIELD DETERMINATION METHOD ON THE EXAMPLE OF CYG X-1**

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



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.

According to Robertson & Leiter, 2003

Black holes → MECO (Magnetic Extremely Compact Object)

Magnetic moment of Cyg X-1 $\mu = 10^{30}$ G cm^3

$B(3R_g) > 10^8$ G

so **Cyg X-1 is MECO**