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On the possible existence of brightness spots on Cyg X-1 supergiant

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We consider the impact of recently detected magnetic field of O9.7 Iab supergiant component of Cyg X-1 X-ray binary system on its atmosphere. We show the magnetic pressure to be comparable with that of the stellar atmosphere matter pressure, which should lead to formation of bright spots on the surface of the star. We have used the simplest estimation of magnetic force influence on Cyg X-1 optical component atmosphere structure and brightness of the spots near magnetic poles. The upper estimation of their brightness contrast (25%) is obtained. We show that the expected spots may be observed both photometrically and spectroscopically. The possibility of magnetic field diagnostics through observation of the spots is briefly discussed.

Keywords: Stars: magnetic fields – Stars: spots – Stars: O-supergiant – Stars: individual (HD 226868 = V1357 Cyg = Cyg X-1)

1 Introduction

The incredibly precise photometric measurements of exoplanet transition events for a great number of Sun-like stars by the *Kepler* space observatory revive attention to brightness spots on stars. Spots on stars, both similar and cooler than the Sun, have definitely a magnetic origin. The spots on hotter magnetic Ap and Bp stars are studied intensively. These stars have strong surface magnetic fields from hundreds up to tens of thousand Gauss. The influence of strong magnetic field on structure and radiation of non-convective model atmospheres of A V and late B V stars has been discussed starting from the pioneer papers by Trasco (1972) and Staude (1972). Great progress has been made over the last decades.

Several years ago, publications about the existence of brightness and magnetic spots on massive OB stars also appeared (Reiners et al. 2000; Cantiello et al. 2009; Cantiello, Braithwaite 2011). It is a result of the progress in spectropolarimetric

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instruments for registration of large-scale magnetic fields on such stars (B = 100–1000 G). It permits revealing the fields on a few dozen OB stars (Donati et al. 2002, 2006; Hubrig et al. 2006; Petit et al. 2008; Grunhut et al. 2009; Karitskaya et al. 2009, Martins et al. 2010; Wade 2012 etc). However, the validity of a number of published results is yet under discussion (Bagnulo et al. 2012).

VLT FORS1 spectropolarimetric measurements point to the presence of a few hundred Gauss magnetic field on Cyg X-1 optical component (Karitskaya et al. 2009, 2010; Bagnulo et al. 2012).

In this paper we consider spots possibly existing in the photosphere of O9.7 Iab supergiant, the optical counterpart of black hole X-ray binary HDE 226868 = V1357 Cyg = Cyg X-1 (the orbital period P = 5.6^d). This system is the prototype of black hole binaries. Therefore it has been and continues to be a target for observers working in all electromagnetic ranges as well as for different kinds of theoretical studies.

Knowledge of this star magnetic field configuration (and its possible variations) may supply crucial information about magnetic accretion on black holes. So searching Cyg X-1 magnetic field is an actual task now. But even the usage of most sensitive spectropolarimetric instruments of the world permits us to measure it only on a rather low confidential level ($\leq (5-6)\sigma$) (Karitskaya et al. 2009, 2010; Bagnulo et al. 2012). Therefore, to discuss, find and use independent methods for its search is currently an actual task. In this paper we consider the possibility of the existence of magnetic spots and discuss some opportunities their observations can open.

2 O-supergiant, the optical component Cyg X-1

The O9.7 Iab supergiant component of Cyg X-1 is responsible for about 95% of the system optical luminosity. The remaining 5% are due to the accretion structure (disc and surrounding gas) near the black hole. The optical spectrum contains O-supergiant absorption lines; the accretion structure emission components exists only in He II 4686 Å and Hα profiles; stellar wind P Cyg components are present in H and He I lines as well as in some other lines (e.g., Karitskaya et al. 2008). Stellar wind $\dot{M} \sim (2\text{–}3) \cdot 10^{-6}\ M_{\rm sun}$/yr (Gies et al. 2003). Chemical peculiarities were found in the supergiant photosphere namely excesses of He, N, Ne, Mg, Si (the elements by CNO- and α-processes) by a factor of 2.5–8 (see Karitskaya et al. 2007a,b; Karitskaya et al. 2011; Shimanskii et al. 2012). It looks like the mixing of matter due in all probability to tidal interaction and mass exchange with the relativistic component at previous and present stages of evolution.

The spectropolarimetric observations with FORS1 at 8.2-m VLT telescope (Paranal, Chile) resulted in detection of a magnetic field in the X-ray binary Cyg X-1 (Karitskaya et al. 2009, 2010). The value of the mean longitudinal magnetic field of the optical component (9.7 Iab supergiant) changes regularly with the orbital phase reaching its maximum of 130 G ($\sigma \sim 20$ G). The measurements based on Zeeman effect were carried through over all observed supergiant photosphere absorption spectral lines. Uniformed pipeline reprocessing of all the FORS1 spectropolarimetric observations (Bagnulo et al. 2012) speaks in favor of the magnetic field existence on the object.

Cyg X-1 optical component model atmosphere was computed by Karitskaya et al. (2005, 2007a) and Shimanskii et al. (2012). The X-ray illumination by "soft" and "hard" spectra, tidal distortion of the stellar shape, non-LTE effects were taken into account. The supergiant parameters: the effective temperature $T_{\rm eff} = 30400 \pm 500$ K, averaged along the surface and gravity acceleration $\log\ g = 3.31 \pm 0.07$, were obtained. The magnetic field influence on the atmosphere structure was not taken into account.

In spite of Cyg X-1 being intensively investigated for over 40 years, a lot of phenomena remain unexplained. The photometric investigation carried through during these years revealed different kinds of variability on different time scales (orbital variations, flares and dips of different types, the so-called precession period 147/294 days, variations on tens of years time-scale, etc.) the nature of some of them remains unclear up to now (e.g., Karitskaya et al. 2000, 2001, 2006). Evidence of irregularities in matter flowing between the components was found. A comparison of photoelectric and X-ray flux variations has shown the existence of a correspondence between optical and X-ray flux variations. Cross-correlation analysis revealed lags of X-ray (2–10 keV) variations in respect to optical variations.

3 Magnetic field influence on stellar atmosphere

In general, the magnetic field affects the stellar atmosphere structure through radiative transfer (by radiation polarizing), the changing opacity via the magnetic line blanketing and the chemical elements diffusion, and also by magnetic forces.

Great progress in these areas has been made over the last decades. According to Shulyak et al. (2005), Khochukhov et al. (2005), Khan and Shulyak (2006 a, b, 2007 a, b) for B less than 1 kG the influence of both, accounting for polarization in radiative transfer and the magnetic line blanketing on the model atmosphere structure and stellar fundamental parameter determination are small enough. Diffusion of elements does affect the general element abundance because of short evolution time and strong macro-turbulence ($V_{\rm macro} \approx 65 \pm 7$ km/s, Shimanskii et al. 2012). So in the case of Cyg X-1 optical component the magnetic force is the main factor necessary to be taken into account.

Discussion of magnetic force influence on atmosphere structure has a long history. Trasco (1972) and Staude (1972) were the first to calculate quasi-static models of the magnetic spots on the surface of non-convective A V magnetic stars and showed that the large spot appears brighter than its photospheric surroundings.

Later Lorentz forces induced by magnetic field variations in non-convective stars were taken into account. Stepien (1978) initiated discussion of possible deformations of the stellar atmosphere produced by Lorentz force which is created by electric currents generated by magnetic field changing inside the star. There are many reasons for the field variations, e.g., slow decay of a fossil magnetic field. Landstreet (1987) concludes that this decay-induced Lorentz force is generally not significant in magnetic Ap and Bp stars. Effects of global meridional circulation are less important than those due to fossil field decay for rotation periods of more than about 4 days (Moss 1984). Among other reasons for appearance of the Lorentz force in the stars with magnetic fields there are ambipolar diffusion, differential rotation etc.

4 Possible brightness spots on Cyg X-1 O-supergiant

Because of complication of detailed magnetohydrodynamic calculation of magnetic force impacts on stellar atmosphere matter only the first attempts to construct 2D and 3D models of magnetic star atmospheres have been made (e.g., Sundqvist et al. 2009; ud-Doula et al. 2013). Moreover, in our case the magnetic field configuration, dynamical fluids in supergiant atmosphere and so on are unknown. Therefore we can make only the simplest estimations. Similar to Staude (1972) we consider essentially cylindrically symmetric magneto-hydrostatic model in the vicinity of magnetic poles.

The mean longitudinal magnetic field averaged over the picture plane is about $\langle B_z \rangle \sim 100$ G in the photosphere of Cyg X-1 optical component (Karitskaya et al. 2009, 2010). The real magnetic field may exceed $\langle B_z \rangle$ and may reach or even exceed 300 G near the magnetic poles.

The equation of hydrostatic equilibrium, which includes the Lorentz force term $\mathbf{F}_L$, has the form

$$\nabla(P_g + P_r) = \rho\mathbf{g} + \mathbf{F}_L, \tag{1}$$

where P_g and P_r are gaseous and radiative pressure correspondingly, $\mathbf{g}$ is gravitation acceleration, ρ is gas density. The Lorentz force can be written as

$$\mathbf{F}_L = -\frac{\nabla\mathbf{B}^2}{8\pi} + \frac{1}{4\pi}(\mathbf{B}\cdot\nabla)\cdot\mathbf{B}. \tag{2}$$

The magnetic field creates in the plasma an isotropic pressure $\mathbf{B}^2/8\pi$ (the first term in eq. (2)) and a tension (the second term) directed along the magnetic lines of force, related to the force line curvature, and tries to straighten them.

As the full solution of the self consistent magnetogasdynamics problem is very complicated, we restricted ourselves to the simplest estimations in the frame of the unipolar cylindrically symmetric circumpolar magnetic spot model in static approximation. Leaving out of consideration the Lorentz force component related to the force line curvature, we can present eq. (1) in the form

$$\nabla(P_g + P_r + \frac{\mathbf{B}^2}{8\pi}) = \rho\mathbf{g}. \tag{3}$$

So in this case including magnetic field in consideration leads to magnetic pressure adding to sum of gaseous and radiative pressures. The resulting total pressure should be used for calculation of model atmosphere.

We compare the magnetic pressure

$$P_m = \frac{\mathbf{B}^2}{8\pi} \tag{4}$$

with the gas pressure, and the sum of gas and radiation pressure in the atmosphere of Cyg X-1 optical component (O-supergiant). For this purpose we used model atmosphere without magnetic field calculated by Karitskaya et al. (2007a) and Shimanskii et al. (2012).

Figure 1 shows the pressure versus optical depth in Cyg X-1 optical component's atmosphere. The common logarithm of Rosseland mean of optical depth τ_R is the abscissa axis. The common logarithm of pressure is shown by the ordinate axis. The

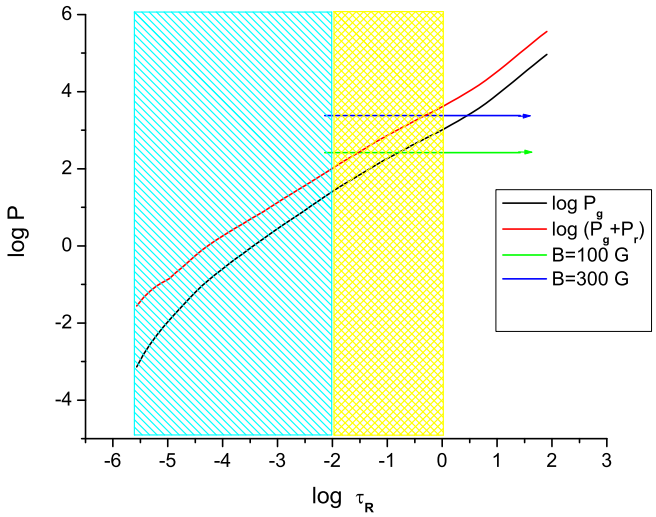


Figure 1 A comparison of gas pressure and the sum of gas and radiation pressure with the magnetic pressure in the atmosphere of Cyg X-1 optical component (the O-supergiant). Shown here is the relation of gas pressure (the black curve) and gas and radiation pressure taken together (the red curve) on the Rosseland mean of optical depth ($\log \tau_{\rm R}$). The horizontal lines indicate levels of the magnetic pressure for magnetic strength B equal to 300 G (blue line with arrow) and 100 G (green line with arrow). The yellow area on the graph marks the area corresponding to Cyg X-1 optical component's photosphere. The cyan shaded area marks the area, corresponding to the stellar chromosphere.

relation of the sum of gas and radiation pressure on $\tau_{\rm R}$ is shown by the red line. The black line shows the relation for gas pressure on $\tau_{\rm R}$. The pressure differences between the relations for the X-ray-illuminated and not X-ray-illuminated atmosphere is small – within the line width.

The horizontal lines indicate the magnetic pressure for magnetic strength B equal to 300 G (blue line with arrow) and 100 G (green line with arrow) in accordance with our spectropolarimetric measurement (Karitskaya et al. 2009, 2010). As photospheric spectral lines were used for it these B values refer to stellar photosphere (near magnetic pole and beyond) marked by yellow area on Figure 1. The cyan shaded area marks the star's chromosphere with the temperature inversion which appears in the case of the "soft" X-ray state (Shimanskij et al. 2012).

Figure 1 shows that the magnetic pressure becomes comparable not only with gas pressure but also with the sum of gas and radiation pressure in the stellar photosphere and may even exceed them near the magnetic poles. Hence, we may expect the magnetic field influence on the matter outflow (the stellar wind), as well as on the accretion flow. The magnetic field structure variability may be responsible for some long-term variations of matter-flow process in this binary system. For example, it may be a reason of the so-called precession $147/294^d$ Cyg X-1 variability (e.g., Kemp et al. 1987).

Near the magnetic poles, where the magnetic pressure forms a significant part of the full pressure, the gas pressure (and so gas density) must be considerably lower

than far from the poles. Consequently, at the poles we may pierce deeper inside and see hotter atmosphere layers. So we may expect the existence of hot spots with slight differences in temperature relative to surrounding areas. Such spots may have an influence on the light curve and spectral line profiles.

We estimate the upper limit of brightness of the suspected spots. As follows from Fig. 1 in the regions of the magnetic poles where $B \approx 300$ G magnetic pressure on the level $\tau = 1$ (in our model without magnetic field) is equal to gas and radiation pressure taken together. So in this stellar atmosphere layer the magnetic pressure is equal to 50% of total pressure P. In the stationary case it means that the gas density must be more than twice lower relative to atmosphere regions without magnetic field. Consequently we may suggest that the atmosphere of the spot is twice more transparent than out of it and we can observe a deeper layer of atmosphere. Namely we can detect radiation produced by the atmospheric layers corresponding to out-of-spot (non-magnetic) ones with twice more optical depth $\tau \sim 2$. For upper limit estimation we suggest that the atmosphere conserves unchanged temperature. Namely we use electron temperature T_e as the function of the Rosseland optical depth $2\tau_{\rm R}$ instead of the $\tau_{\rm R}$ according to Shimanskij et al. (2012).

It should be mentioned that in our case of the hot supergiant atmosphere, where Thompson scattering is very important, optical depths in optical range (5000 Å) are close to the Rosseland mean $\log \tau_{\rm R}$. Therefore for the estimation it is not necessary to distinguish between the two values and the index for τ can be omitted. As the result we get the upper limit for the relative continuum brightness of $\Delta I/I \simeq +0.25$ of magnetic spot near 5000 Å on the Cyg X-1 optical component for observations normally to stellar surface.

5 Discussion

We compare the upper limit we have obtained for Cyg X-1 optical component magnetic spots relative to brightness with the estimations given by Staude (1972) and Trasco (1972). Staude gives $\Delta I/I \approx 0.02$–0.05 for A V stars. Trasco gives far greater values, up to 12%, for B6V–B8V stars. Those values do not contradict our uppermost estimation 25% for the O9.7 Iab star.

Consequently we may hope that our reasonings are qualitatively correct. In the case of magnetic poles not coinciding with stellar rotation poles, the brightness spots may influence the light curve and the shapes of spectral line profiles. Oblique magnetic field takes place for the majority of magnetic stars and also with greatest probability for Cyg X-1 supergiant (Karitskaya et al. 2009, 2010).

If the real $\Delta I/I$ is not far from our upper limit, then the ground-based optical broad bend photometry (ordinal precision of 1%) is able to detect spots of a size of 1/3 of the stellar radius with 3σ significant level. For high precision ground-based photometry ($\sim 0.5\%$) it is able to find spots of about 1/4 of the stellar radius. In our case of O-supergiant the stellar radius being about 10^{12} cm the spots of a size of about 2×10^{11} cm may be detected. The field of higher multipole configuration forms the spots of lesser size. But the magnetic fields of stars are mostly dipolar rarely showing quadrupolar or octupolar configurations (Landstreet, Mathys 2000).

Because magnetic fields of non-convective stars are fossil, the higher harmonics have enough time to decay (e.g., Landstreet 1987; Valyavin et al. 2004).

The situation with supergiants is not clear. They are suspected to have a thin subsurface convective zone (Maeder 2009; Cantiello et al. 2009; Cantiello, Braithwaite 2011). In massive O-stars with solar element abundances such zones are formed at an early stage of star evolution. Therefore it is quite possible that during the star evolution up to supergiant stage the magnetic dynamo may produce fields of several hundred Gauss. In this case the magnetic fields may have a complicated topology with magnetic tubes, loops etc., and as is the case with the Sun, produce small-size spots with high magnetic field strengths B. In this case, very high precision photometric observation of the spots with space telescopes analogous to the *Kepler* observatory is needed. So searching of spots can be considered as an independent instrument of magnetic field analysis for O-supergiants such as in Cyg X-1.

As the magnetic field is most likely inclined to the axis of rotation, one may expect a corresponding photometric variability. The V1357 Cyg (Cyg X-1) brightness variation is rich in various events not yet fully explained (see, e.g., Karitskaya et al. 2000, 2001). To reveal the brightness spots it is necessary to achieve the photometric precision of several 0.001^m. In any case the mean orbital curve obtained over several years is not symmetrical and somewhat differs from the theoretically expected tidally distortion light curve (see, e.g., Karitskaya et al. 2001). The differences are about 0.01^m. It is necessary to investigate it more precisely.

Also this is related to the shape of spectral line profile variations. The expected effect of magnetic field on Balmer lines is ~ 0.01 to continuum (e.g., Valyavin et al. 2004). Besides, brightness spots with other atmosphere parameters distort the spectral line profiles because of stellar rotation. It may create variable profile asymmetry. To find this effect it is necessary to have observations with signal-to-noise ratio ≥ 300. During our spectral observations on the 6-meter telescope we revealed year-to-year spectral line (e.g., H_β) profile variations in close orbital phases. But it may be the result of other reasons (e.g., clumpy stellar wind) so it is necessary to continue investigations.

6 Conclusion

The observed magnetic field leads to an estimation of the magnetic pressure in Cyg X-1 O-supergiant photosphere as comparable with model atmosphere gas and radiative pressure, exceeding them in the area surrounding the magnetic poles. It leads to conclusion about significant influence of magnetic field on the atmosphere structure, at least in the circumpole area.

It is emphasized that in the case of Cyg X-1 optical component (as well as other non-convective stars with $B \leq 500$ G) the magnetic field influence on the stellar atmosphere structure through the radiative transfer (by radiation polarizing), the changing opacity via the magnetic line blanketing and the chemical elements diffusion can be neglected. So the magnetic force is the main factor necessary to be taken into account.

As the full solution of the self consistent magnetogasdynamics problem is very complicated, we did not go beyond the simplest estimations in the frame of the unipolar

cylindrically symmetric circumpolar magnetic spot model in static approximation. Taking into account the magnetic pressure leads to a decrease of gas density and matter opacity. As a result, within the spot we observe deeper and hotter layers. The upper estimation of the relative brightness $\Delta I/I \simeq +0.25$ of magnetic spot near 5000 Å on the Cyg X-1 optical component.

The dipolar or quadrupolar magnetic field can create large size bright spots which can be studied by ground-based optical photometry. In the case of magnetic field inclined to the stellar rotation axis the suspected variability may achieve about 1%. The field of higher multipolar configuration (produced by dynamo) can form the spots of lesser size and may be revealed only by space telescopes. Besides, spots may be revealed in spectral line profile variability. Searching of spots can be considered as an independent tool of magnetic field analysis for O-supergiants such as in Cyg X-1.

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