What can we learn about the stellar wind of massive stars from studying spin evolution of the X-ray pulsar OAO 1657-415

V.Yu. Kim and N.R. Ikhsanov

1Pulkovo Observatory, St. Petersburg, 196140 Russia
2Saint Petersburg State University, St. Petersburg, 198504 Russia
3Special Astrophysical Observatory, Nizhny Arkhyz, 369167 Russia

E-mail: kim@gao.spb.ru, ikhsanov@gao.spb.ru

Abstract. The persistent X-ray pulsar OAO 1657-415 is associated with a wind-fed High Mass X-ray Binary system and shows a peculiar spin evolution. On a timescale of more than 30 years it is observed to experience a regular spin-up which is superposed on episodic and chaotic variations of the period at a very high rate. We explore a possibility to explain the spin evolution of the pulsar in terms of Magnetic Levitation Accretion scenario in which the neutron star captures material from a magnetized stellar wind of its massive companion and accretes matter from a non-Keplerian magnetized disk (Magnetic Levitating disk or ML-disk). We show this scenario to be applicable if the magnetic field in the wind at a distance of binary separation lies in the interval $20 - 70$ mG.

1. Introduction
Persistent X-ray pulsars represent a subclass of pulsars whose X-ray luminosity has not been observed to vary by more than an order of magnitude [1]. A majority of these sources are associated with High Mass X-ray Binaries (HMXBs) composed of a massive O/B-type star and a magnetized rotating Neutron Star (NS). The X-ray emission of these systems is usually powered by a wind-fed accretion onto the NS. The appearance of the X-ray sources depends on physical conditions in the matter captured by the NS and, hence, these pulsars can be considered as “laboratories” for studying parameters of stellar wind ejected by their massive companions.

This is a complimentary method to the currently used spectral analysis of UV radiation, which allows to evaluate terminal wind velocity and the mass-loss rate by the massive stars [2, 3]. An application of the method to determination of magnetic field in the wind of the massive component of the HMXB OAO 1657-415 is discussed in this paper.

OAO 1657-415 has initially been discovered as a point-like X-Ray source by [4] and recognized to be $P_s \simeq 38.22$ s pulsar by [5]. It was later associated with the $P_{orb} \simeq 10.44$ d HMXB [6] composed of a NS and a B0 – 6Iab supergiant and located at the distance of $6.4 \pm 1.5$ kpc [7]. The X-ray luminosity of the source is smoothly varying by a factor of 8 around its average value $L_x \simeq 3 \times 10^{36}$ erg s$^{-1}$, [8]. A presence of the $\sim 36$ keV cyclotron line in its X-ray spectrum suggests the surface magnetic field of the neutron star to be $B_{ns} \simeq 3 \times 10^{12}$ G [9].
Figure 1. Evolution of spin period OAO 1657 from 1979 to 2015 received by "HEAO-1", "Temna", "Ginga", "Einstein" [10], "Integral" [11], "Fermi GMB" [12]

2. Observed spin evolution
The pulsar is observed to experience a regular spin-up (see fig. 1) at the average rate $\dot{\nu}_{su}(g) = (7.7 - 8.9) \times 10^{-13} \text{Hzs}^{-1}$ [11, 8]. The spin period of the pulsar since its discovery decreased by $\Delta P \simeq 1.312 \text{s}$ to its currently observed value 36.9 s.

The regular spin-up trend is superimposed with rapid spin-up/spin-down episodes. These spin variations occur at the spin-up, $\dot{\nu}_{su}^{(1)} \simeq 6.07 \times 10^{-12} \text{Hzs}^{-1}$, and spin-down, $\dot{\nu}_{sd}^{(1)} \simeq -3.92 \times 10^{-12} \text{Hzs}^{-1}$ rates and show no correlation with intensity variations of the system X-ray emission [13].

3. Regular spin-up
The observed regular spin-up of the pulsar implies that the average spin-up torque exerted on the NS by the accreting matter is $< K_{su} > \geq 2\pi I \dot{\nu}_{su}^{(g)}$, where $I$ is the moment of inertia of the NS. On the other hand, the average rate of transfer of angular momentum into the Roche lobe of a NS by the material which the NS of mass $M_{ns}$ captures at the Bondi radius, $r_G = \frac{2GM_{ns}}{v_{t\text{rel}}^2}$, is limited to $< K_{su} > \leq \xi M\Omega_{orb}r_G^2$. Here $v_{t\text{rel}}$ is the relative velocity of the NS to the surrounding material, $M$ is the mass-transfer rate between the system components, $\Omega_{orb} = \frac{2\pi}{P_{orb}}$ is the orbital angular velocity and $\xi$ is the efficiency parameter accounting for dissipation of the angular momentum due to density and velocity gradients in the accretion flow inside the Bondi radius.

Solving inequality $2\pi I \dot{\nu}_{su}^{(g)} \leq \xi M\Omega_{orb}r_G^2$ for $v_{t\text{rel}}$ one finds that the observed regular spin-up

1 It is a product of the maximum possible specific angular momentum of the material captured by the NS at the Bondi radius, $\Omega_{orb}r_G^2$, with the mass captured by the NS in a unit time, $M$, corrected by the factor $\xi \leq 1$.
of the pulsar implies that the relative velocity of the NS satisfies the condition \( v_{rel} \leq v_0 \), where

\[
v_0 \simeq 273 \text{ km s}^{-1} \times \xi_{0.2}^{1/4} \left( \frac{M}{2 \times 10^{16} \text{ g s}^{-1}} \right)^{1/4} \left( \frac{P_{\text{orb}}}{10.44 \text{ d}} \right)^{-1/4} \left( \frac{\nu_{\text{ns}}^4}{8 \times 10^{-13} \text{ Hz s}^{-1}} \right)^{-1/4}
\]

Here \( \xi_{0.2} = \xi / 0.2 \) is normalized according to [14], \( m = M_{\text{ns}} / 1.4 M_\odot \) and \( I_{45} = I / 10^{45} \text{ g cm}^2 \).

### 4. Accretion scenario

Traditional quasi-spherical and Keplerian disk accretion scenarios encounter major difficulties explaining the observed rates of spin evolution of the pulsar during the spin-up/spin-down episodes [13]. Indeed, the maximum possible spin-down rate of the NS which can be expected for the parameters of OAO 1657-415 in these scenarios,

\[
\dot{\nu}_{sd}^{(0)} = \frac{k_t M \omega_s r_{\alpha}^2}{2 \pi I} \simeq -10^{-13} \text{ Hz s}^{-1} \times k_t \frac{p_{30}^{8/7} M_{16}^{3/7}}{m^{-2/7} I_{45}^{-1} P_{37}^{-1}},
\]

is almost an order of magnitude smaller than the spin-down rate inferred from observations of the spin-down episodes. Here \( k_t \leq 1 \) is the efficiency parameter, \( \omega_s = 2\pi / P_s \) is the angular velocity of the NS and \( r_{\alpha} = \left( \mu^2 / M \sqrt{2GM_{\text{ns}}} \right)^{2/7} \) is the Alfvén radius, which is assumed to be the radius of the magnetosphere of a NS in the traditional accretion scenarios. \( \mu = (1/2)B_{\text{ns}} R_{\text{ns}}^3 \) is the dipole magnetic moment and \( R_{\text{ns}} \) is the radius of the NS and \( P_{37} = P_s / 37 \text{ s} \).

A situation in which the observed rates of spin evolution exceed the maximum possible rate predicted by the traditional accretion scenarios is rather common among pulsars in HMXBs [15]. It can be improved by incorporating the magnetic field of the accreting material, \( B_r \), into the model. The magnetic energy associated with this field, \( B_r^2 / 8\pi \), increases rapidly as the initially quasi-spherical accretion flow is approaching the NS and reaches the dynamical pressure of the flow at a distance

\[
R_{\text{sh}} = \beta_0^{-2/3} r_c \left( \frac{c_{s0}}{v_{\text{rel}}} \right)^{4/3},
\]

which is referred to as Shvartsman radius [16, 17]. Here \( \beta_0 = \beta(r_c) = 8\pi \rho_0 c_{s0}^2 / B_{00}^2 \) is the ratio of a thermal to magnetic pressure at the Bondi radius, \( \rho_0 = \rho(r_c) \) is the density, \( c_{s0} = c_s(r_c) \) is the sound speed and \( B_{00} = B_f(r_c) \) is the magnetic field in the stellar wind of the massive companion at the Bondi radius.

Being controlled by its own magnetic field the accretion flow inside the Shvartsman radius changes its geometry from quasi-spherical to a non-Keplerian magnetized disk [18, 19] (which in later studies is referred to as Magnetic Levitating disk, or ML-disk [20]). The torque exerted on the NS from the ML-disk in this case [20],

\[
K_{\text{ml}} = \frac{k_t \mu^2}{(r_{\text{ma}} r_{\text{cor}})^{3/2}} \left( \frac{\Omega_f (r_{\text{ma}})}{\omega_s} - 1 \right),
\]

is large enough for the expected spin-down rate of the NS in OAO 1657-415,

\[
\dot{\nu}_{sd}^{(ml)} = \frac{K_{\text{ml}}}{2 \pi I} \simeq -8 \times 10^{-12} \text{ Hz s}^{-1} \times m^{-8/13} \alpha_0^{-3/13} P_{37}^{-1} r_{13}^{3/13} M_{16}^{6/13} \mu_{30}^{17/13},
\]

to be in excess of the observed value by more than a factor of 2. Here \( k_t \) is the efficiency parameter, \( r_{\text{cor}} = (GM_{\text{ns}} / \omega_s^2)^{1/3} \) is the corotation radius, \( \Omega_f \) is the angular velocity of matter in the ML-disk and [15]

\[
r_{\text{ma}} = \left( \frac{c m_p^2}{16 e k_B} \right)^{2/13} \frac{\alpha_0^{2/13} \mu^{6/13} (GM_{\text{ns}})^{1/13}}{T_0^{2/13} M_{4/13}^{3/13}},
\]
is the inner radius of the disk which plays a role of the magnetospheric radius of the NS within this so called Magnetic Levitation Accretion scenario (MLA-scenario). Here c is the speed of light, \( m_p \) is the proton mass, \( e \) is the electric charge of an electron, \( k_B \) is the Boltzmann constant and \( T_0 \) is the temperature of matter at the inner radius of the ML-disk \( (T_0 = T_0/10^6 \text{K}) \). The parameter \( \alpha_R \) is the ratio of the effective diffusion coefficient at the magnetospheric boundary to the Bohm diffusion coefficient and \( \alpha_{0.1} = \alpha_R/0.1 \) (for discussion see [20] and references therein).

Hence, the observed spin evolution of OAO1657-415 can be explained within the MLA-scenario provided the relative velocity of a NS is limited as \( v_{rel} \leq \upsilon_0 \) and stellar wind of the massive star in this system is magnetized. Constrains for the validity of this explanation are discussed in the next sections.

5. Magnetization of the stellar wind
As recently shown by Ikhsanov and Mereghetti [20] the MLA-scenario can be realized if \( R_{sh} \geq \max\{r_s, r_{circ}\} \), where \( r_{circ} \) is the circularization radius. Under these conditions the magnetic field of the accreting material prevents formation of a Keplerian disk in the system and changes the flow geometry from a quasi-spherical to ML-disk. Solving this inequality for \( v_{rel} \) yields

\[
v_{ca} < v_{rel} < v_{ma},
\]

where

\[
v_{ca} \simeq 160 \text{ km s}^{-1} \times \xi_{0.2}^{3/7} \beta_0^{1/7} m^{3/7} (\frac{P_{\text{orb}}}{10.44 \text{ d}})^{-3/7} (\frac{c_0}{10 \text{ km s}^{-1}})^{-2/7} \]

and

\[
v_{ma} \simeq 540 \text{ km s}^{-1} \times \beta_0^{-1/5} m^{12/35} \mu_{30}^{-6/35} M_{16}^{3/35} (\frac{c_0}{10 \text{ km s}^{-1}})^{2/5}. \]

As we have seen in Sect.3, the observed regular spin-up of OAO1657-415 implies that the relative velocity of a NS is limited as \( v_{rel} \leq \upsilon_0 \), where \( \upsilon_0 \) is expressed by Eq. (1). This allows us to set an upper limit to \( \beta_0 \). Indeed, according to condition (7), the MLA-scenario can be realized in the system only if \( v_{ca} \leq \upsilon_0 \). Otherwise the magnetic field of the accreting material would not be able to prevent formation of a Keplerian disk. Combining Eqs. (1) and (9) and solving inequality \( v_{ca}(\beta_0) \leq \upsilon_0 \) for \( \beta_0 \) one finds that the MLA-scenario in OAO1657-415 can be realized if \( \beta_0 \leq \beta_0^{max} \)

\[
\beta_0^{max} \simeq 50 \times m^{1/2} \xi_{0.2}^{-5/4} f_{45}^{-7/4} M_{16}^{7/4} \left(\frac{c_0}{10 \text{ km s}^{-1}}\right)^2 \left(\frac{P_{\text{orb}}}{10.44 \text{ d}}\right)^{5/4}. \]

A lower limit to \( \beta_0 \) can be derived by taking into account that the regular spin-up of a NS within the MLA-scenario can be expected only if the angular velocity of material at the inner radius of the ML-disk (see Eq. 22 in [20]), \( \Omega_{l}(r_{ma}) \simeq \xi \Omega_{\text{orb}} (r_s/R_{sh})^2 \), exceeds the angular velocity of the NS itself, \( \omega_s \). Solving inequality \( \Omega_{l}(r_{ma}) \geq \omega_s \) for \( \beta_0 \) and using Eq. (3) one finds \( \beta_0 \geq \beta_0^{min} \), where

\[
\beta_0^{min} \simeq 4 \times m^{-8/7} \xi_{0.2}^{-5/4} P_{37}^{-5/4} M_{16}^{-2/7} \left(\frac{c_0}{10 \text{ km s}^{-1}}\right)^2 \left(\frac{P_{\text{orb}}}{10.44 \text{ d}}\right)^{5/4}. \]

The velocities estimated above are plotted in Fig. 2 versus \( \beta_0 \). As seen from this figure the relative velocity for all points within the interval \( \beta_0^{min} \leq \beta_0 \leq \beta_0^{max} \) is smaller than \( \upsilon_{ma} \). This indicates that the modeling of the accretion process in OAO1657-415 within the MLA-scenario is basically applicable.
Finally, using the range of possible values of the parameter $\beta_0$ one can also evaluate the magnetic field strength in the stellar wind of the massive companion at the distance of binary separation. Using the above given definition of $\beta_0$ one finds

$$B_{f0} = \left(\frac{2M v_0^3 c_0^2}{(GM_{\text{ns}})^2 \beta_0}\right)^{1/2}.$$  

Then, putting $\beta_0 = \beta_{0}\max$ and $\beta_0 = \beta_{0}\min$ to this equation one gets $B_{f0}\min \leq B_{f0} \leq B_{f0}\max$, where

$$B_{f0}\min \simeq 19 \text{ mG} \times \dot{M}_{16}^{1/2} \left(\frac{\beta_{0}\max}{50}\right)^{1/2} \left(\frac{c_{0}}{10 \text{ km s}^{-1}}\right) \left(\frac{v_0}{273 \text{ km s}^{-1}}\right)^{3/2}$$

$$B_{f0}\max \simeq 70 \text{ mG} \times \dot{M}_{16}^{1/2} \left(\frac{\beta_{0}\min}{4}\right)^{1/2} \left(\frac{c_{0}}{10 \text{ km s}^{-1}}\right) \left(\frac{v_0}{273 \text{ km s}^{-1}}\right)^{3/2}$$  

Thus, the peculiar spin evolution of OAO 1657-415 can be explained within the MLA-scenario provided the relative velocity of the NS in this system does not exceed $v_0$ given by Eq. (1), and the magnetic field in the stellar wind of the massive component at the distance of orbital separation lies in the range $20 - 70 \text{ mG}$.

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