On the wind accretion model of GX 301-2

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Abstract. We illustrate the evolution of the peculiar behavior of the high mass X-ray binary GX 301-2, through the wind accretion model. We found that the donor of this system has 43 M\textsubscript{\odot} and clearly it experienced of a mass exchange. As a result, the low terminal velocity of the wind from donor (1200 km/s), slow rotation and the relatively low luminosity (3.1 \times 10^{35} \text{erg/s}), can easily fed the neutron star via the stellar wind with enough accretion matter. This will lead to explain the observed X-rays. It has been shown that the characteristics of mass-loss rate through stellar winds would reasonably be expected to alter the changes in wind velocity by X-rays.

1. Introduction
The wind-fed magnetized neutron star of GX 301-2 is a High Mass X-ray Binary (HMXB) system, accreting from the dense wind of the B-type companion\cite{1-2}. As a result, emitting the persistent X-rays. The main physical parameters of this system like, slow spin period of $P_{\text{spin}} \approx 690$ s with orbital period of $P_{\text{orb}} \sim 41.5$ d, and high eccentricity $e \sim 0.5$ (see \cite{3} for full details and references). The nature of accreting pulsars with long pulse periods is still poorly understood \cite{4-7}. However, GX 301-2 shows a strong cyclotron line at an energy of $\sim 42.4^{+3.8}_{-2.5}$ keV\cite{8}, thus the magnetic field is $4.7 \times 10^{12}$ G \cite{5,6}.

We should note that the strong energy variation in cyclotron line, can be occurred during the different phases of the X-ray pulse, and regions with different magnetic fields are observed\cite{9}. This peculiar behavior, is against all odds X-ray characteristics of their progenitor population.
of disk-fed supergiant X-ray binaries, which are detected as bright persistent X-ray sources with typical $L_x = 31.5 \times 10^{35} \text{erg/s}$.

The aim of this work is to provide a reinforce calculation of the accretion model, through a wind driven accretion model which is able to explain the peculiar behavior of the GX 301-2 during the entire stellar evolution track based on a mass and its mass loss at zero-age main sequence stars stage in their binary evolution.

2. The model

We use the standard wind model for typical SG stars developed by[10]. The magnetic field of NS can be estimated according to Eq. (2) in [10] as,

$$B_{NS} = \frac{2^{5/12} \pi^{-7/6} \zeta^{1/2} G^{5/6} M_{NS}^{5/6} R_{NS}^{-2} \dot{M}^{1/2} P_s^{7/6}}{4.46 \times 10^{13} \text{G}}$$

we assume that the mass of NS is 1.4 $M_\odot$, and radius of NS is 10 km. $\zeta \sim 0.5$, is the ratio of accretion velocity to the free-fall velocity.

We assume the Bondi-Hoyle-Littleton accretion[11], to estimate the mass accretion rate onto the NS as

$$\dot{M} = \rho_w \cdot R_{acc}^2 \cdot v_{rel},$$

where $\rho_w$ is the density of the wind during spherical wind, $R_{acc}$ is the accretion radius (Bondi radius). $v_{rel}$ is the relative velocity of the wind which is a combination between wind velocity ($v_w$) and orbital velocity $v_{orb}$

We adopt the standard formula by[12] for the wind velocity $v_w$, which assumed a stationary, homogeneous, and spherically symmetric outflow,

$$v_w = v_\infty \left(1 - \frac{R_d}{a}\right)^{\beta}$$

We assume $\beta$ which is a free input parameter to be $\beta = 1$ as in Ref.[13]. $v_\infty$ denotes the terminal velocity of the wind.

By combining these equations, we got

$$\dot{M} = \left(\frac{G M_{NS}}{r}\right)^2 \dot{M}_w \cdot v_{rel}/v_w.$$  

The mass accretion rate can be derived from the X-ray luminosity, so $\dot{M}$ could be known. We adopt the mass loss-rate given by[14]. An overview of all processes which we shall take into account is given in[15,16].

3. Discussions

Our method based on the equations, gives a relationship between $v_w$ as a function of $B_{field}$ (see Fig. 1). The different accretion regimes (A) to (E) are divided by dashed lines. (A)supersonic inhibition regime ($r_m > r_a, r_{co}$), (B)subsonic inhibition regime ($r_{co} > r_m > r_a$), (C)supersonic propeller regime ($r_a > r_m > r_{co}$), (D)subsonic propeller regime ($r_{co}, r_a > r_m, \dot{M} < \dot{M}_c$), where
\( \dot{M}_c \) denotes the critical limit where radiative cooling starts working\(^{[17]} \) and (E)direct accretion regime. The horizontal solid lines denote the wind velocity given by \( v_{\text{inf}} \)\(^{[14]} \).

With these settings, we vary the mass loss rate of the donor (\( \dot{m}_w \)), terminal velocity of the wind \( v_{\text{inf}} \) to correspond the observational stellar properties. We note that, when the system locates in direct accretion regime, it can emit bright X-rays and be observed as a persistent HMXB.

As we can shown, the wind velocity is too fast to cross to the vertical line given by cyclotron lines\(^{[15]} \) in the direct accretion regime (shaded region). As a result, it strongly suggests that the wind velocity from the donor in GX 301-2 is much slower and more angular momentum can be transferred to the system.

We further investigated the evolution of this system in \( v_{\text{wind}} - P_{\text{spin}} \) diagram. These parameters greatly affect the model of wind-fed binary system and can be constrained during the binary evolution\(^{[18,19]} \). It’s seems to be a more suitable variable for the comparison for this system at different mass-lose rates (see Fig. 2). This relation follows from the relation between the robust data of NS magnetic field, combined with \( P_{\text{spin}} \). The diagram appears to qualitatively explain the system’s behavior. However, the the sudden changes in the wind density which may lead to the switching from one accretion regime to the other. It should be noted that, the eccentricity of the orbit (\( e \leq 0.5 \)) would lead also to a slight variations in the orbital separation (and consequently in \( v_{\text{wind}} \)), which enhances the intrinsic variability of the stellar wind and its ability to lead to a phase transitions across regimes\(^{[20–22]} \).

4. Conclusions

The slow stellar wind model for GX 301-2 resulting in a specific disk formation associated with angular momentum, is likely to be caused by the increased mass accretion rate. This may provide the clear evidence that magnetic field of \( 4.7 \times 10^{12} \) G is linked to the relatively low luminosity (\( 3.1 \times 10^{35} \text{erg/s} \)) corresponding to periastron passage. This interpretation is based on its emission from accretion in high-energy X-rays and the mass-loss rate through stellar winds. In addition, it could help us in understanding how the mass transfer leads the instability in the magnetized X-ray binaries from the surrounding.

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Figure 1. Wind velocity as a function of the magnetic field of GX 301-2 at different mass-loss rates. The two horizontal solid lines denote the range of terminal velocity (at high ~1500 km/s and at low ~700 km/s). The vertical line shows the derived magnetic field from cyclotron lines. In the shaded region (E), the system can be understood with our model and observed as Be-HMXB.

Figure 2. The schematic diagram of a typical small wind with spin period for GX301-2.
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