Propeller regime of the accretion onto young stars in the ballistic approach

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Abstract. The form of the outflows generated during the interaction of the accretion disc with the tilted stellar magnetosphere in the propeller regime is studied in the ballistic approach. The problem is solved analytically. Different ways of the flux expansion are considered. The results are applied to the description of the narrow absorption details observed in the spectra of young stars in a blue wing of the sodium D Na I resonance lines.

1. Introduction

In the spectra of some young stars (RZ Psc [1], [2], MWC 480 [3] and others) unusual discrete absorption components are seen in the blue wing of the sodium D Na I lines (Figure 1). The number, shape and radial velocities of these components vary from night to night.

![Figure 1](image_url)

Figure 1. Two spectra of MWC 480 [3] in the neighborhood of the sodium resonance doublet. The radial velocities of the individual components of the lines are indicated. The strong changes in the helium 5876 Å line are seen in the spectrum.

We assume [4] that absorption components may be a result of the interaction of an accretion disc with a magnetosphere in the propeller regime. The possibility of this regime was first noticed by Illarionov and Sunyaev [6] during the study of an accretion onto neutron stars. It is realized when the effective radius of the magnetosphere exceeds a corotation one. In this case...
the rotating magnetosphere of the star rejects the falling matter. As a result the accretion flow onto the star may be rather weak. We suppose that the outflowing matter may cause the narrow absorption components at the intersection of the light of sight with the different parts of the gas stream.

Taking into consideration the expression for the radius of the Alfven surface [7] we can draw a conclusion that a decrease in the mass accretion which is usual during the young stars evolution may lead the accretion process to turn into the propeller regime (the radius of the Alfven surface $r_A \sim M^{-2/7}$, where $M$ is the mass accretion rate).

2. Form of the outflows
In this work we consider a case when a dipole magnetic field of the star is misaligned with the rotation axis of the star (and the disc). In this case the magnetically accelerated matter forms two spiral outflows which originate from the disc-magnetosphere boundary [8]. The outflowing matter may be ejected to an infinite distance. However, returning into the accretion disc is also conceivable.

We suppose that the matter is accelerated to a velocity $V_0 = \beta V_f$ (where $V_f$ is the circular velocity of the ejection point and $\beta$ is parameter of the model) and ejected forming with the disc plane an angle $\alpha$. We assume that the direction of the outflow in the ejection point is orthogonal to the radius-vector. At the same time the region where the matter is launched from the disc is rotating with the angular velocity of the magnetosphere and the star $\Omega$. As a result rotating spiral tracery is formed. The form of these outflows can be described analytically in the ballistic approach [9].

Let us introduce a system of Cartesian rotating coordinates centered at the star’s center. The $X$ axis is directed to the ejection point. The $Y$ axis lies in the disc plane. $Y$ and $Z$ axes are directed to the outflow direction. In the case of $\beta < \sqrt{2}$ when the matter returns into disc the expression for the outflows form is:

\[
\begin{align*}
    x &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sin E \cos \alpha \sin \theta + \frac{r_c}{2 - \beta^2} (\cos E - (\beta^2 - 1)) \cos \theta \\
    y &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sin E \cos \alpha \cos \theta - \frac{r_c}{2 - \beta^2} (\cos E - (\beta^2 - 1)) \sin \theta, \\
    z &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sin E \sin \alpha
\end{align*}
\]

where

\[
\theta = \Omega \frac{E - (\beta^2 - 1) \sin E}{\kappa} \left( \frac{r_c}{2 - \beta^2} \right)^{\frac{3}{2}}. \tag{2}
\]

Here $r_c$ is the corotation radius, $\kappa = \sqrt{GM}$ the gravitation parameter which is equal to root square from the gravitation constant multiplied by the star’s mass, $E \in [0, 2\pi]$ is the eccentric anomaly.

In the case of $\beta > \sqrt{2}$ when the matter is ejected to an infinite distance the expression is slightly different:

\[
\begin{align*}
    x &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sinh H \cos \alpha \sin \theta + \frac{r_c}{\beta^2 - 2} \left( (\beta^2 - 1) - \cosh H \right) \cos \theta \\
    y &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sinh H \cos \alpha \cos \theta - \frac{r_c}{\beta^2 - 2} \left( (\beta^2 - 1) - \cosh H \right) \sin \theta, \\
    z &= \frac{\beta r_c}{\sqrt{2} - \beta^2} \sinh H \sin \alpha
\end{align*}
\]

where

\[
\theta = \Omega \left( \frac{\beta^2 - 1}{\kappa} \sinh H - H \right) \left( \frac{r_c}{\beta^2 - 2} \right)^{\frac{3}{2}}. \tag{4}
\]

$H \in [0, +\infty)$ is an analog of the eccentric anomaly for the hyperbola.
Figure 2. Forms of the outflows in the cases of $\beta < \sqrt{2}$ (left panel) and $\beta > \sqrt{2}$ (right panel).

### 2.1. Asymptotic solution

When the ejected matter does not return onto the disc ($\beta > \sqrt{2}$) there is an asymptotic form of the formula (3). We pay attention to the circumstance that $\sinh H$ and $\cosh H$ grows fast with an increase in $H$. Moreover, when $H$ is large $\sinh H \approx \cosh H$. After simple transformations, we obtain that at large $H$ a spiral turns out on the cone with the star on its top:

$$x^2 + y^2 \frac{1}{1 + \beta^2 (\beta^2 - 2) \cos^2 \alpha} - \frac{z^2}{\beta^2 (\beta^2 - 2) \sin^2 \alpha} = 0. \tag{5}$$

Hence, when the observer looks through the cone’s side there might be few discrete components from different spiral’s turns.

### 3. Outflow expansion

For the modeling of the outflow expansion two different ways have been used. In the first way we assume that the cross section of the stream expands isotropically with the sound speed:

$$c = \sqrt{\frac{\gamma R}{\mu} \sqrt{T}}. \tag{6}$$

here $\gamma$ is the adiabatic index (5/3 for a monatomic gase), $R$ the molar gas constant, $\mu$ the molar mass, $T$ the temperature.

Figure 3. Cross section of the outflow in the case of the expansion with the sound velocity for $\beta < \sqrt{2}$. $R_*$ is the radius of the star. Dotted lines show the channel from the star to the observer.
In the second case we modeled trajectories of the particles thrown with some velocity dispersion. For the size of this dispersion we took the root mean square speed of the matter in the disc:

\[ V_\tau = \sqrt{\frac{3R}{\mu} \sqrt{T}}. \] (7)

Figure 4. The same as on the figure 3 for the expansion caused by the dispersion in the velocities.

As can be seen from figures 3–5 both methods show close results in the beginning. Later there are some differences. We suppose that the both ways are important and take part in the real expansion. The expansion with the sound speed may be more important in the beginning of the flow whereas the dispersion in the velocities should take larger part in the extrinsic spiral turns. The mechanism of the expansion influences the components shape. It should be studied in detail with more observation data.

Each crossing of the channel from the star to the observer with the outflow gives one absorption component.

Figure 5. The same as on the figures 3–4 in the case \( \beta > \sqrt{2} \).

4. Radial velocities

Radial velocities of the components depend on the radial velocity of the outflow which can be easily obtained from the integrals of motion:

\[ v_r = \sqrt{\frac{2}{r} + \frac{\beta^2 - 2}{R_0} - \frac{\beta^2 R_0}{r^2}}, \] (8)

here \( r \) is the distance from the star. This allows us to get radial velocities from the model and compare them with the observations. When \( \beta < \sqrt{2} \) the radial velocity decreases until zero in the point where the matter contacts the disc. Otherwise the minimum velocity is positive.
5. Conclusion
The model considered above demonstrates a possibility to explain the narrow discrete absorption components of the sodium resonance doublet lines in the spectra of some young stars. The more detailed discussion of the accretion onto the young stars in the propeller regime and the derivation of the equations presented above will be given in papers [4] and [9].

In this model we does not consider an acceleration of the matter. Therefore, it does not provide the full description of the process, but makes further researches of this spectral peculiarity well grounded. The more detail model can predict the number and radial velocities of the components. To make more definite conclusions about the nature of the components we need the spectral monitoring of these stars. After this monitoring we’ll have a possibility to specify the model and compare it with the observations.

The analytical results may be also used for the description of some other problems such as outflow modeling from any rotating source. It might be disc winds or jets from binary systems or active galactic nucleus.

Acknowledgments
We thank the referee, D. P. Barsukov, for the useful comments that improved the paper.

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