HYDRODYNAMIC AND RADIATIVE MODELING OF TEMPORAL Hα EMISSION V/R VARIATIONS CAUSED BY DISCONTINUOUS MASS TRANSFER IN BINARIES

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ABSTRACT

Hα emission V/R variations caused by discontinuous mass transfer in interacting binaries with a rapidly rotating accreting star are modeled qualitatively for the first time. The program ZEUS-MP was used to create a non-linear three-dimensional hydrodynamical model of a development of a blob of gaseous material injected into an orbit around a star. It resulted in the formation of an elongated disk with a slow prograde revolution. The LTE radiative transfer program SHELLSPEC was used to calculate the Hα profiles originating in the disk for several phases of its revolution. The profiles have the form of a double emission and exhibit V/R and radial velocity variations. However, these variations should be a temporal phenomenon since imposing a viscosity in the given model would lead to a circularization of the disk and fading-out of the given variations.

Key words: binaries: close – circumstellar matter – stars: emission-line, Be

Online-only material: animation, color figure

1. INTRODUCTION

The existing modeling of V/R variations was based almost exclusively on the model of a slowly revolving elongated envelope around a single star, identified in physical terms with one-armed oscillations in the disk (see, e.g., Struve 1931; Johnson 1958; McLaughlin 1961a, 1961b; Okazaki 1997; Fišť & Harmanec 2006). The envelope was assumed to originate from an equatorial mass outflow due to a critical rotation of the star. In this paper, we present the first preliminary investigation of the alternative idea that an elongated envelope around a star originates from a discontinuous and short mass transfer from a companion in a binary system. This transfer may occur in eccentric binaries during a periastron passage. Moreover, such inflow of material could also be caused by density enhancement in stellar wind in the form of coronal mass ejections from a rapidly rotating star having a quadrupole term in its gravitational potential.

In Section 2, we present a hydrodynamic model of discontinuous mass transfer. Radiative modeling of an Hα profile originating in a formed disk around an accreting star and the measurement of its V/R and radial velocity (hereafter RV) variations is presented in Section 3.

2. HYDRODYNAMIC MODELING OF DISCONTINUOUS MASS TRANSFER IN A BINARY

We decided to carry out the first modeling of V/R changes imposed by a discontinuous mass transfer presented as a blob of a gaseous material set into an orbit around a rapidly rotating star having a quadrupole term in its gravitational potential. As detailed below, we use several simplifications that can be challenged but we do not think that they seriously affect the results on a qualitative basis. The main simplification is the assumption of an inviscid gas. The viscosity of an orbiting gas, which is not included in this first model, is expected to destroy any asymmetry in the disk and all observed effects should be only temporal. Another simplification that could be criticized is the assumption of an optically thin environment. In our defense, we would like to mention that in the early stages of attempts to model V/R variations, Huang (1973) used a model based on the assumption of an optically thin envelope while Křiž (1976) performed a similar study assuming optically thick envelopes. While Křiž’s line profiles look more realistic, both authors obtained a reasonable description of the V/R changes since the velocity field and the asymmetry of the envelope were decisive ones. On the other hand, we should emphasize that we make no assumptions about the disk in our model and gradually build it via a non-linear hydrodynamic modeling of the evolution of discontinuous mass inflow.

To simulate a hydrodynamic development of a blob of mass originating from discontinuous mass transfer from a secondary, we used the program ZEUS-MP, a multiprocessor clone of the original program ZEUS-3D (Vernaleo & Reynolds 2006). The computational domain was a hollow cylinder that had the following dimensions in cylindrical coordinates (z, r, ϕ):

\[ -0.1 \, R_\ast \leq z \leq 0.1 \, R_\ast, \]
\[ R_\ast \leq r \leq 70 \, R_\ast, \]
\[ 0 \leq \phi \leq 2\pi. \]

At its center, we placed a rapidly rotating star with a mass of \( M_\ast = 11 \, M_\odot \) and a radius of \( R_\ast = 5.5 \, R_\odot \) with a gravitational potential of \( \Phi(z, r, \phi) \) given by

\[ \Phi = -\frac{GM_\ast}{\sqrt{r^2 + z^2}} \left[ 1 + \frac{k_s f^2}{3} \frac{R_\ast^2}{r^2 + z^2} \left( 1 - \frac{3z^2}{r^2 + z^2} \right) \right], \]

where \( k_s \) denotes an apsidal motion constant and \( f \) is the ratio of a surface rotation to a critical Keplerian rotation:

\[ f = \frac{\Omega(R_\ast)}{\Omega_K(R_\ast)}. \]
Figure 1. Density structure in an equatorial plane of the disk (left) and the H$_2$ line profiles resulting from it (right) for various phases of the prograde rotation of the elongated density enhancement. Gas particles in the disk orbit counterclockwise and the direction toward an observer is to the right along a horizontal line.

(An animation and a color version of this figure are available in the online journal.)
For our simulation, we chose these parameters to be $k_2 = 0.03$ and $f = 0.95$. Circumstellar matter consists of inviscid, non-self-gravitating ideal gas with a constant temperature $T_d = 10,000$ K. The dynamical evolution of the gas is described by standard hydrodynamical equations for an isothermal case

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p - \rho \nabla \Phi,$$

where $\rho$, $p$, $\mathbf{v}$, and $\Phi$ are the gas density, pressure, velocity, and the gravitational potential, respectively. $D/Dt$ denotes the Lagrangian derivative. Throughout the simulation, we used dimensionless scaled units (denoted with tilde) for length $\tilde{l}$, mass $\tilde{m}$, and time $\tilde{t}$. These are related to physical units as follows:

$$\tilde{l} := \frac{l}{R_\ast}, \tilde{m} := \frac{m}{M_\ast}, \tilde{t} := \sqrt{\frac{GM_\ast}{R_\ast^3}}t,$$

where $G$ denotes the universal gravitational constant. Note that with this choice we have $\tilde{G} = 1$ and the computational domain has the dimensions $-0.1 \leq \tilde{z} \leq 0.1$, $1 \leq \tilde{r} \leq 70$, and $0 \leq \tilde{\psi} \leq 2\pi$.

As initial conditions for density and velocity components we impose

$$\tilde{\rho} = 10^{-4}, \tilde{v}_z = \tilde{v}_r = 0, \tilde{v}_\phi = \tilde{r}^{-3/2},$$

where $\tilde{v}_\phi$ corresponds to a Keplerian velocity. We imposed periodic boundary conditions in the $\phi$ and $z$ directions. For an inner boundary condition at the surface of the star ($\tilde{r} = 1$), we used a slip boundary condition $v_r = v_z = 0$, $v_\phi = \tilde{f}$ with $\tilde{f}$ defined as above. Regarding an outer boundary condition, we used a pressure-free outflow boundary condition.

To simulate a short discontinuous mass inflow to an accreting star, we injected a compact ($\tilde{r}_{inj} \in [40, 42]$, $\tilde{\psi}_{inj} \in [0, 0.2]$, $\tilde{z}_{inj} \in [-0.1, 0.1]$) blob of mass $\tilde{\rho} = 1$ at 80% of the Keplerian velocity ($\tilde{v}_z = \tilde{v}_r = 0$, $\tilde{v}_\phi = 0.8\tilde{r}^{-3/2}$) into an initial “interstellar vacuum” and followed its evolution over time.

Our simulation led to the formation of an elongated accretion disk around the central star. A density structure in an equatorial plane of the disk and its time evolution are shown in the left panels of Figure 1, which shows several selected frames from a hydrodynamic animation that is available in the online version of the journal. Material in the disk orbits counterclockwise and the direction toward an observer in all panels is to the right along a horizontal line. It can be seen that a denser region forms near an apocenter of the elliptical disk due to crowding of the orbiting material there. The elongated disk undergoes a slow prograde rotation with a period of about 16 years.

The prograde rotation of the disk is caused by the quadrupole term of the gravitational potential. This result is in qualitative agreement with several papers that studied the influence of the quadrupole term of the gravitational potential of fast-rotating stars on a precession rate of the disks around them (see, e.g., Savonije & Heemskerk 1993; Okazaki 1996; Fišr & Harmanec 2006). However, the linear one-armed oscillation numerical simulations presented in these papers use different values for the input parameters and therefore it is not possible to perform a quantitative comparison of our precession period with their results. Moreover, Fišr & Harmanec (2006) showed that a precession period is dependent on many free parameters (one of them is the term $k_2f$, which describes the rate of stellar distortion due to its rotation) and the dependence on some parameters is quite strong (see Figures 3–9 in Fišr & Harmanec 2006). Therefore, by choosing different values for the given input parameters, it is possible to obtain a precession period in a range from $\sim 1$ year to several tens of years.

3. Radiative Modeling of the Hα Profile

To model the emission profiles of the Hα line originating in the disk, we used the program SHELLSPEC (Budaj & Richards 2004). It solves a radiative transfer along the line of sight in an optically thin environment assuming LTE. Only scattered light from the central star is taken into account, however. The star itself was treated as a blackbody with a temperature of $T_\ast = 22,000$ K. We chose the view of an observer located in the
equatorial plane, i.e., an inclination of 90°. The resulting profiles of the Hα line for various phases of the prograde rotation of the disk are displayed in the right panels of Figure 1. The modeling leads to double-peaked emission-line profiles. The denser region in the disk emits more radiation and its revolution around the central star combined with the rotation of the disk particles result in the $V/R$ changes.

We imported a representative selection of the model Hα line profiles into SPEFO (Horn et al. 1996; Škoda 1996) and measured their $V/R$ ratios and the RVs on the wings of the emission. Time variations of the $V/R$ ratios and the RVs for one cycle of the prograde revolution of the disk are displayed in Figure 2. Both quantities have a sinusoidal development and they are in phase.

4. CONCLUSION

We attempted to test the idea that temporal Hα $V/R$ variations can be caused by discontinuous mass transfer from a companion star in a binary. As an initial simple representation of discontinuous mass transfer, we injected a blob of mass into an orbit around a rapidly rotating star and followed its evolution via three-dimensional hydrodynamic modeling, which led to the formation of an elliptical disk with a slow prograde revolution. We expect that a similar result would be obtained when injecting a blob of “new” mass into an already developed circular disk. An LTE radiative model of the Hα line led to a double-peaked emission profile in which $V/R$ ratios and RVs undergo cyclic variations in phase. However, these variations should be only temporal since the viscosity of an orbiting gas should circularize the disk if there is an absence of mass transfer from a secondary as was also shown by Bisikalo et al. (2001). Therefore, the $V/R$ variations should also gradually fade out.

Nevertheless, we are aware that this first attempt to test the given idea was considerably simplified. Besides the already mentioned assumption of inviscid isothermal gas, the simplification also involves how the discontinuous mass transfer from the companion is represented. Moreover, it is expected that an inclusion of the attractive force of the orbiting companion (also absent in the present model) could speed up the disk revolution, resulting in a shorter cycle length. Therefore, we intend to improve our model taking into account the points mentioned above in a future study.

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