Structure of the Circumbinary Envelope Around a Young Binary System

P. V. Kaigorodov, D. V. Bisikalo, A. M. Fateeva, and A. Yu. Sytov

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Abstract

The structure of a circumstellar envelope around a young binary T Tauri star is considered. The supersonic orbital motion of the system components in the envelope gas leads to the formation of bow shocks around the star. Two- and three-dimensional numerical modeling indicates an important role of these shocks in the formation of the structure of the circumbinary envelope. In particular, for systems with circular orbits, the size of the central region of the envelope that is not filled with matter (the gap) is essentially determined by the parameters of the bow shocks. These modeling results are supported by comparisons of the obtained estimates for the gap parameters with observations.

1 Introduction

In an early stage of their evolution, close-binary systems pass through a stage of accreting matter from a common envelope, which is essentially a remnant of the protostellar cloud. Of all stars located in this stage, the best studied are binary T Tauri stars – young stars that are just entering the main sequence. Observations of these stars in the radio and infrared indicate that their envelopes consist of gas (∼99%) and dust (∼1%). The gaseous component consists of molecular hydrogen H\textsubscript{2} and He, together with a number of heavier molecules – O\textsubscript{2}, CO, CO\textsubscript{2}, H\textsubscript{2}O and others. These envelopes have a disk-like form; their thickness grows with distance from the center of mass of the system, and the velocities of matter in the envelope display Keplerian distributions. The presence of a region in the central part of the disk that is free from matter – so-called gap – is also indicated by the observations, at least for some systems.

The formation of gaps around binary stars was first studied by Artymowicz and Lubow [1,2], who also carried out numerical simulations of the accretion of matter from a protoplanetary disk onto the binary. They concluded that the leading role in the formation of inner gaps in the protoplanetary disks of binary stars was played by Lindblad resonances. In spite of the obvious influence of resonances on the structure of the circumbinary envelope, it follows from [1] and the table that the theoretical sizes of such gaps estimated using the method of [1] lie systematically below the observed values.

One possible explanation for the systematically larger sizes of the observationally derived gaps is failure to include certain gas-dynamical effects in earlier studies.
Figure 1: Dependence of the gap radius $R$ for T Tauri stars on their orbital periods $P$. The circles with numbers show the observed radii for various systems, identified according to their numbers in the table [1]. The "×" show estimates of gap radii corresponding to the location of resonances [1]. The dashed line shows the minimum possible gap radius, corresponding to the distance from the center of mass to the outer radius of the accretion disk of the primary component. The triangles show the gap radii derived from the results of gas-dynamical modeling.

of their formation. The SPH method was used to numerically model the gas dynamics in [1,2], with a very small number of particles, due to the limited power of computers available at that time. As follows from the figures presented in [1,2,13], SPH particles are virtually absent from the inner region of the envelope, making it impossible to adequately model the gas dynamics of the matter in this region. However, gas-dynamical computations carried out using grid methods [14,15] show the formation of a complex flow pattern in the inner regions of the envelope, including the accretion disks around the stars and a system of shocks. Among the most prominent structural elements of the flow are bow shocks formed due to the supersonic orbital motion of the components of the system and their surrounding accretion disks through the gaseous envelope.

The goal of the current paper is to study the influence of these bow shocks on the flow structure in the inner regions of the circumstellar envelope and, in particular, on the formation of gaps in the envelope.
2 The numerical model

Our model of a binary star includes the system components and the circumstellar gaseous disk, and is described by the masses of the stars $M_1$ and $M_2$, their radii $R_1$ and $R_2$, the distance between the component centers of mass $A$, the outer radius of the circumstellar disk $R_{\text{ext}}$, the equatorial density of the disk $\rho_{\text{disk}}$, and the temperature of the disk $T_{\text{disk}}$.

At the initial time, the spatial region was filled with gas with density $\rho_{\text{disk}}$ and temperature $T_{\text{disk}}$. Free-inflow conditions were specified at the surfaces of the components. Constant density and a constant velocity corresponding to the Keplerian value at the given distance from the center of mass of the system were specified at the outer boundary of the region. The region inside the stars and outside the computational region, $r > R_{\text{ext}}$, were excluded from the computations.

The modeling was carried out in a rotating coordinate system tied to the binary star. We described the gas flows in the system using a system of Euler equations for gravitational, adiabatic gas dynamics, closing them with the equation of state of an ideal gas. The temperature in the solution was held constant and equal to the initial temperature of the initial disk, 2656K. The radius of the stars was taken to be $1R_\odot$ in all computations.

We solved the system of equations numerically using a RoeOsherEinfeldt finite-difference scheme similar to those in [16–18]. All the two-dimensional computations were performed in a 12A × 12A computational region on a uniform grid with 2200 × 2200 cells. The three-dimensional computations were performed in a 12A × 12A × 1.5A computational region on a non-uniform grid with 480 × 480 × 224 cells. The grid used for the three-dimensional computations varied such that the resolution between the components was no worse than in the two-dimensional solutions.

3 Results of the numerical simulations

Figure 2 shows the distribution of the density and velocity vectors in the equatorial plane of the system, and Figure 3 the density distribution along the line joining the components. The centers of mass of the secondary and primary components
Figure 2: Distribution of the logarithm of the density in the equatorial plane of the system for the two-dimensional computations (gray scale and contours).

are at the positions (0,0) and (A,0), respectively. Accretion disks form around the components, bounded by the radii of the corresponding last stable orbits. Outgoing shocks with the form of diverging spirals form ahead of the accretion disks (the rotation of the system is in the counterclockwise direction). At a distance $R \sim 2 \div 3A$ from the center of mass, the wave formed by the main component intersects itself, giving rise to a large number of smaller waves and fragments. The strongly fragmented wave continues to expand, reaching the edge of the computational region. The difference in density between the rarified gap region and the wave is a factor of $\sim 10^3$. The density difference inside the wave can reach factors of $5 \div 7$. The shape of the rarified region is slightly non-circular: its extent along the line joining the components is $\sim 20\%$ larger than in the perpendicular direction.

Figure 4 shows the region near the binary star on a larger scale. This clearly shows that the bow shocks of the two components have slightly different shapes. The bow shock ahead of the accretion disk of the secondary component is weaker and displays a lower degree of winding than the wave associated with the primary. The velocity field in the rarified region indicates a fairly complex flow pattern.

At some time, the bow shock of the primary component begins to expand. This shock intersects itself after $\sim 1.25$ windings – the outer edge of the diverging shock collides with the inner edge of the following winding. Moreover, this shock becomes perturbed when it collides with the bow shock of the secondary. These interactions
Figure 3: Distribution of density along the line joining the components. The letter G denotes the gap region.

give rise to a large number of shocks that interfere with each other in the disk.

The bow shock associated with the secondary is also spiral in form. However, this shock is appreciably weaker, since the secondary is located in the region of wave rarefaction that arises behind the bow shock of the primary. Moreover, this wave is disrupted when it collides with the denser shock of the primary after it has completed less than a fourth of a revolution around the system.

Figure 5 shows the flow structure near the binary star obtained from the three-dimensional modeling. These results show all the flow elements obtained in the two-dimensional case, with their sizes and positions also being similar to those obtained in the two-dimensional computations.

4 Conclusions

Our gas-dynamical solutions show that the gas velocity in the rarified region near the binary star differs appreciably from a Keplerian distribution. This suggests that the flow in this region is determined primarily by gas-dynamical phenomena. The strongest influence on the flow is exerted by the bow shock that forms due to the motion of the accretion disk of the more massive component; accordingly, the radial extent of this wave determines the size of the inner gap.

The numerical modeling we have considered here shows that the gap radius is \( \sim 2.4A \) for all the systems studied. Figure 4 shows the values of the gaps obtained from observations of various types of stars, together with those obtained from gas-dynamical modeling. In two cases (stars 1 and 6), the gaps obtained from the
Figure 4: Same as Fig. 2 for the region near the binary star. The vectors show the velocity field. Roche equipotential surfaces are shown by the dashed curves.

modeling are larger than the corresponding resonance radii; however, the resonance radii are larger for stars 3 and 4. The best agreement with observations is obtained for star 5, and the worst agreement for star 2. Finally, practically all the gap radii obtained from the modeling results (except for that for star 5) lie below the observed gaps.

Most importantly, we note that stars 3 and 4, whose gaps lie below the positions corresponding to resonances, have large orbital eccentricities. The numerical code we used is intended for modeling systems with circular orbits. To obtain our solutions, we modeled systems analogous to stars 3 and 4, but with circular orbits whose radii corresponded to the semi-major axes of these stars. The SPH modeling carried out in the works [1,2] shows that the cut-off radius due to the resonances grows when the eccentricity is increased, and can exceed $2.4A$—the characteristic extent of the bow shock. Accordingly, the formation of the gap in systems with high eccentricities may be due to resonances, while the main role in systems with close to circular orbits is played by the bow shock.

We also note that the gap sizes derived from observations are determined in part by the results of modeling the spectra of these systems. Such modeling usually assumes Keplerian motion of matter in a protoplanetary disk. However, as the gas-dynamical modeling shows, the flow is appreciably non-Keplerian, at least in inner parts of the disk. Moreover, the presence of shocks and dense rings in the disk must
Figure 5: Same as Fig. 4 for the three-dimensional computations.

influence the form of the observed spectra. The lack of allowance for these factors may lead to systematic errors in the derived gap parameters

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