Disc wind in the HH 30 binary models

L. V. Tambovtseva¹ and V. P. Grinin¹,²
¹Main Astronomical Observatory Pulkovo, Pulkovskoe shosse 65, St. Petersburg 196140, Russia
²The Astronomical Institute of the St. Petersburg University, Petrodvorets, St. Petersburg, 198904, Russia

ABSTRACT

Recent interferometric observations of the young stellar object (YSO) HH 30 have revealed a low velocity outflow in the ¹²CO J=1-2 molecule line (Pety et al. 2006). We present here two models of the low velocity disc winds with the aim of investigating an origin of this molecular outflow. Following Andlada et al. (2006) we treated HH 30 as a binary system. Two cases have been considered: i) the orbital period \( P = 53 \) yrs and ii) \( P \leq 1 \) yr. Calculations showed that in the first case the outflow cone had a spiral-like structure due to summing the velocities of the orbital motion and the disc wind. Such a structure contradicts the observations. In the second case, the outflow cone demonstrates a symmetry relatively to the system axis and agrees well with the observations.

Key words: circumstellar matter – stars: individual: HH 30 – binaries: close.

1 INTRODUCTION

The Herbig–Haro object HH 30 is a well–known YSO with a flared circumstellar (CS) disc seen practically edge–on (Burrows et al. 1996; Ray et al. 1996) and highly collimated optical jets propagating perpendicular to the disc, firstly observed by Mundt & Frid (1983). The star itself is not visible, it is detected only through radiation scattered by the CS disc. According to Pety et al. (2006) (hereafter P06), HH 30 is a star with a mass of \( 0.45 M_\odot \), spectral type around of M1 and age of \( (1 - 4) \times 10^6 \) years. The millimeter observations showed that it is surrounded with the CS Keplerian disc with the radius of about 420 AU and the mass of about \( 4 \times 10^{-3} M_\odot \). Optical observations showed the disk of about 450 AU in diameter (Burrows et al. 1996).

Since 1996 this object has been a subject of intense investigations by different authors (Bacciotti et al. 1999; Stapelfeldt et al. 1999; Wood et al. 2000, 2002; Cotera et al. 2001; Watson & Stapelfeldt 2004). Optical observations with the Hubble Space Telescope (HST) as well as the millimeter interferometry revealed a strong variability and asymmetry in the radiation coming from the CS disc. Burrows et al. (1996) detected changes in the brightness ratio of the upper and lower nebulae between 1994 and 1995, and the presence of a weak lateral brightness asymmetry. Stapelfeldt et al. (1999) found that in 1998 one side of the disc was four times brighter than the other.

The interpretation of the HH 30 brightness variability and asymmetry has a great importance. Stapelfeldt et al. (1999) excluded large-scale motions of the matter in the outer disc as a possible reason of such variations. They argued that the outer disc acts as a screen, on which moving illumination patterns are projected from the inner disc or the central star. They suggested two mechanisms which are able to form such light changes: (i) illumination by the star with bright accretion hot spots (Wood & Whitney (1998)) and (ii) presence of voids or clumps in the inner disc casting beams or shadows onto the outer disc. Each of these mechanisms can produce asymmetry in the nebulae brightness, which shifts from one to another side of the disc. Watson & Stapelfeldt (2004, 2007) did not find the period to be correlated with the stellar rotation period or any other period. According to them, the variability of HH 30 has the more complex character and caused by the changes in the CS extinction in the inner disc. Tambovtseva and Grinin (2008) showed that such extinction variations can be caused by the dust component of the azimuthally non-homogeneous disc wind. A knowledge of the asymmetry mechanism would give a possibility to determine in detail a structure of the nearest regions of the young star that has not been done with the help of the telescopes. Also this permits us to study more definitely the physical processes leading to formation of such structures.

One of the main result of the HH 30 study obtained during recent years, was the detection of the slow matter outflow in the \( ^{12}\text{CO}(2-1) \) molecule line by P06. This outflow was highly asymmetric (one-sided) in spite of the presence

* E-mail: tamb@gao.spb.ru (LVT); grinin@gao.spb.ru (VPG)
of relatively symmetric jets, and originated from the inner parts of the disk, had a conical morphology with a 30° half opening angle and a radial velocity of about 12 km s\(^{-1}\). P06 concluded that the observed CO emission arose from material that has been directly launched from the disc and moved ballistically in the first few 100 AU from the star; the re-collimation could occur at the distances larger than 1000 AU. According to their interpretation, the high-velocity optical jet and low-velocity outflow are associated with different parts of the disc wind. The former corresponds to its densest part (<1AU) and the latter to its outer part (5 - 15 AU). The mass loss rate of the outflow \(\dot{M}_w\) was estimated as \(6.3 \times 10^{-6} M_\odot\) yr\(^{-1}\); it is almost 60 times more than that of the jet equaled to \(\approx 10^{-9} M_\odot\) yr\(^{-1}\). Because however of their velocity differences it follows that a majority of the kinetic energy of the disc wind \((L_w = 6 \times 10^{31} \text{ erg} \ \text{c}^{-1})\) is contained in the narrow collimated jet, while the bulk of the mass loss occurs via the low-velocity wind component.

Recently Anglada et al. (2007) revealed periodic changes in the jet’s trajectory and connected this with the binarity of HH 30. They concluded that the structure of the HH 30 jet can be described by a wiggling ballistic jet, arising either by the orbital motion of the jet source (i.e., the secondary) around the primary or by precession of the jet axis because of the tidal effects of the secondary. In the first scenario, the orbital period is 53 years, and the sum of masses is 0.25 - 2 \(M_\odot\). In the second scenario, the mass of the jet source (i.e., the primary) has to be \(\sim 0.1 - 1 M_\odot\), the orbital period is less than 1 year, and the mass of the companion less than a few \(\times 0.01 M_\odot\). In both scenarios the separation of the binary does not exceed 18 AU. Knowing the size of the flared disc the authors conclude that this is circumbinary rather than circumstellar disc.

In this paper we model the disc wind in the binary system in the framework of the two scenarios suggested by Anglada et al. (2007). In section 2 we briefly formulate the problem for the first scenario and present results of calculations, in section 3 we do the same for the precession scenario. Then we discus results and make the conclusion.

### 2 DISC WIND IN THE YOUNG BINARY SYSTEM

We consider the wind from the low-mass secondary companion moving in a circular orbit in the young binary system. The companion accretes matter from the remnants of the protostellar cloud, the so-called circumbinary (CB) disc. In detail the model is presented in our early paper (Grinin & Tambovtseva 2002). Here is a brief description of the model. Following Artyomowicz & Lubow (1996), we treat the low-mass companion as the main accretor. The wind particles, consisting of gas and dust in the standard proportion, are ejected from the surface of its accretion disc within a cone having fixed inner and outer angles. It is supposed that in the frame of the secondary, the outflow has an azimuthal symmetry. In the coordinate system of the primary, the wind becomes asymmetric due to the vector summing the particles and the orbital motion velocities. Trajectories of the wind particles in the gravitational field of the primary have been calculated in the ballistic approximation. We imitated the quasi-continuous process by ejecting the particles in a small and equal time interval. Computation stopped when the particles reached the outer radius \(R_{out}\) or the equatorial plane of the binary.

In order to reproduce the molecular outflow in HH 30 we used parameters estimated by P06: the outflow matter is mainly located on the thin walls of a cone with a semi-opening angle of 30°. The radial velocity \(V_w = 12 \pm 2\) km/s, the tangential velocity component is absent. The mass loss rate \(\dot{M}_w = 6.3 \times 10^{-8} M_\odot\) yr\(^{-1}\).

Taking this into account, we adopt the following parameters for our model: mass of the primary \(M_*=0.45 M_\odot\), and the eccentricity \(e = 0\). In order to provide the orbital period of 53 yrs, the radius of the orbit \(r_0 = 11\) AU has been chosen. The initial radial velocity of the wind particle, in units of the corresponding Keplerian velocity, was an input parameter and varied from 2 to 5. The Keplerian velocity at \(r_0 = 11\) AU is about 6 km s\(^{-1}\). Three models of the outflow are presented in Fig. 1, and their parameters given in the Table (models A, B, C).

![Figure 1. The distribution of the wind particles in the common envelope created by the disc wind of the secondary component in the models A, B and C (the XZ projection). The left panel: the computed particles distribution; the right panel: the same after smoothing procedure (details are in the text). Letters refer to the model. Distances X and Z are given in units of the orbital radius.](image-url)

## Table (models A, B, C).

| Model | Parameters | Description |
|-------|------------|-------------|
| A     | \(M_*=0.45 M_\odot\), \(e = 0\) | High-velocity wind component |
| B     | \(M_*=0.45 M_\odot\), \(e = 0\) | Low-velocity wind component |
| C     | \(M_*=0.45 M_\odot\), \(e = 0\) | Precession scenario |

Thus, in the models considered below, the common parameters are the parameters of the orbit and a zero tangential component of the wind velocity \(U\). The models differ with radial velocities of the wind particles \(V\) and angles of their ejection \(\theta\) (Table 1). The angles are counted from the symmetry axis. Figure 1 (the left panel) displays the computed distribution of the wind particles in the common en-
Table 1. Parameters of the models

| Model | $\theta$  | $V$ | $U$ |
|-------|-----------|-----|-----|
| A     | 30        | 3   | 0   |
| B     | 45        | 3   | 0   |
| C     | 30        | 5   | 0   |
| D     | 30 - 40   | 2   | 1   |

Figure 2. Isodensity contours for models A, B and C. The details are in the text.

Figure 3. The wind geometry.

3 PRECESSION SCENARIO

Anglada et al. (2007) suggested a second scenario: the wiggling jet structure is caused by precession of the jet axis due to tidal perturbations from the low mass companion. In this case the binary system is very close. The jet source is an accretion disc of the primary and the question arises: where does the low velocity wind come from? P06 concluded that for a single star, the source of the biconical molecular outflow lies on the surface of the accretion disc at 5 - 15 AU from the center. This means, that in the close binary with the low-mass companion, located at the distance of $\lesssim 1$ AU from the central star, the inner disc of the primary cannot be a source of the molecular outflow, because the launched region would be near the inner boundary of the CB-disc. In the case of a circular orbit, one can assume that the inner boundary of the CB-disc possess an axial symmetry. Therefore, the initial conditions for the disc wind will not depend on the azimuth, and, thus, an outflow produced by such a wind will be axially symmetric. In this scenario, the wind particles simultaneously start from the inner CB-disc in small time intervals. As above, calculations have been made using a ballistic approach. Trajectories of the particles have been calculated exactly as in the first case, differing only in initial and boundary conditions, and with that the orbital motion of companions did not influence anyhow the particles kinematics. The radius of the orbit $r_0 = 0.75$ AU. With such a radius and the mass of the star $0.45 \, M_\odot$, the period of the system is about 1 year. According to calculations by Artymowicz & Lubow (1994) the inner radius of the CB-disc $r_{CB}$ is 3-4 times greater than the orbital radius $r_0$. We adopted $r_{CB} = 4r_0 \approx 3AU$. In this case the Keplerian velocity at the inner radius of the CB-disc is about 13 km/s.

Table 1 includes parameters of the model D considered in the second scenario. The radial and tangential components of the initial velocity of the wind particles are expressed in units of the Keplerian velocity at $r_{CB}$. The particles are ejected in the cone constrained with the angles $\theta_1 = 40^\circ$ and $\theta_2 = 30^\circ$ (Fig 3). As calculation show, in this case the disc wind produces axially symmetric outflow with parameters close to those observed. The isodensity map calculated for such an outflow is presented in Fig. 4.

Let us estimate the optical depth of the disc wind $\tau$...
in this model of HH 30. Denote $\Delta \theta = \theta_1 - \theta_2$. Taking into account, that the thickness of the molecular outflow cone is small (P06), we assume that $\theta_1 \approx \theta_2 \equiv \theta$. Then, $\Delta \theta \ll \theta$. With the help of the Eq. (1) from the paper by Grinin & Tambovtseva (2006), one can obtain the optical depth of the cone “wall” along the radius $r_1 r_2$, which at the small $\gamma$ can be replaced by the radius $r_1 r_2$ which is parallel to the disc plane and intersects the disc axis at the distance $h$ from the point $O^\prime$ (Fig. 3):

$$\tau = \frac{M_\text{w}}{V_\text{w}} \frac{\kappa_\lambda}{2\pi h \sin \theta}. \quad (1)$$

Here $M_\text{w}$ and $V_\text{w}$ are the mass loss rate and the velocity of the disc wind material respectively, $\kappa_\lambda$ is a coefficient of absorption by the dust component of the disc wind at the wavelength $\lambda$. It should be noted, that when deriving this formula we took into consideration, that the outflow in HH 30 occurs with a strong deviation from mirror symmetry: the major part of the matter flows in the upper cone.

Substituting the values of $M_\text{w}$ and $V_\text{w}$ in the expression (1) and adopting $\theta = 30^\circ$ and $\kappa_\lambda = 250 \text{ cm}^2/\text{g}$ (that corresponds to the wavelength $\approx 5000 \text{ Å}$ for the CS dust), we obtain the optical depth in the base of the disc wind material respectively, $\tau$ is a coefficient of absorption by the dust component of the disc wind at the wavelength $\lambda$. If we assume that the molecular outflow originates from the outer part of the disc wind, launched at a few AU from the star, another problem arises: how to explain the interval between the jet and the outflow, in other words, the lack of detected material at intermediate velocities and angles? The binary status of HH 30 helps to avoid this difficulty. In both models of the binary system considered in the present paper, the jet and the disc wind originate from different sources. It should also be taken into account that in the binary system with the low-mass companion a cavity free of matter arises due to the gravitational perturbations (Artymowicz & Lubow 1994), therefore, this pause may be naturally explained.

Based on the analysis of the observed (Hartigan et al. 1995) and computed forbidden lines, Kwan & Tademaru (1995) conclude that a substantial fraction of the emitting wind particles has low velocities. Can the low-velocity part of the disc wind, originating from the warm disc (Ferreira, Dougados & Cabrit 2006, Ferreira 2007), produce such a molecular outflow as observed in HH 30? This question needs to be explored. In the case of a single star a discontinuity in launch regions of jets and disc winds would be a more serious issue than in the case of the binary system, but the disc wind problem in binaries remains to be investigated.

$^1$ It should be noted that entrainment mechanism would lead to the conical structure of the molecular outflow but arguments mentioned above prevent its application.

4 DISCUSSION

Let us put aside the problem of the binarity of HH 30 and discuss other possible mechanisms for the formation of the molecular outflow. A comprehensive overview of the molecular outflow models is presented by Arce et al. (2007) (see also the references therein). All of them can be separated into four broad classes: (1) wind-driven shells, (2) jet-driven bow shocks, (3) jet-driven turbulent flows, and (4) circulation flows. In the first three models the molecular outflow is entrained by an underlying wind or jet, in the fourth, it is formed by deflected infalling matter.

Pety et al. (2006) discuss the second entrainment scenario as a possible mechanism of the outflow origin. According to this mechanism, the observed outflows consist in ambient molecular gas that has been put into motion by large bow shocks propagating down the underlying jets (e.g. Gueth & Guilloteau 1999). This mechanism explains well outflows observed on large scales ($\gg 1000 \text{ AU}$). In the case of HH 30, the outflowing molecular gas is continuously collimated down to the very close vicinity of the star, on spatial scales that are smaller than the disk size. This implies that the outflow arises from material that has been directly launched from the disk surface. Also, it is difficult to understand why CO emission is absent in the southern lobe. In the framework of the jet-driven flow models this means that properties of the ambient medium in the north and south directions differ strongly. Thus, the main arguments against entrainment and pro disc wind scenario are a conical geometry, a radial velocity near the launching region, and a lack of CO emission in the south lobe. For these reasons, P06 ruled out the jet-driven flows from considerations in favor of disc wind mechanism. 

Nevertheless, if we assume that the molecular outflow originates from the outer part of the disc wind, launched at a few AU from the star, another problem arises: how to explain the interval between the jet and the outflow, in other words, the lack of detected material at intermediate velocities and angles? The binary status of HH 30 helps to avoid this difficulty. In both models of the binary system considered in the present paper, the jet and the disc wind originate from different sources. It should also be taken into account that in the binary system with the low-mass companion a cavity free of matter arises due to the gravitational perturbations (Artymowicz & Lubow 1994), therefore, this pause may be naturally explained.

Based on the analysis of the observed (Hartigan et al. 1995) and computed forbidden lines, Kwan & Tademaru (1995) conclude that a substantial fraction of the emitting wind particles has low velocities. Can the low-velocity part of the disc wind, originating from the warm disc (Ferreira, Dougados & Cabrit 2006, Ferreira 2007), produce such a molecular outflow as observed in HH 30? This question needs to be explored. In the case of a single star a discontinuity in launch regions of jets and disc winds would be a more serious issue than in the case of the binary system, but the disc wind problem in binaries remains to be investigated.

$^1$ It should be noted that entrainment mechanism would lead to the conical structure of the molecular outflow but arguments mentioned above prevent its application.
5 CONCLUSION

We calculated the trajectories of the disc wind motion using a ballistic approach within the framework of the two binary system scenarios for HH 30. In the first model, the disc wind originates from the accretion disc of the secondary companion; in the second model, the source of the low-velocity disc wind is the inner region of the circumbinary disc.

Calculations showed that in the first case, the matter outflow had a spiral-like structure due to the orbital motion of the wind source around the primary. Such a structure does not agree with the axially symmetric cone morphology of the outflow in HH 30 observed by Pety et al. (2006). The cone outflow geometry is typical for the second model, in which the well collimated and highly accelerated jet, and the slow molecular outflow, originate from the different regions of the binary system: the jet from the inner disc of the primary, and the molecular outflow from the inner boundary of the CB disc. The dust component of the azimuthally non-homogeneous disc wind could be a source of the variable extinction both in the case of HH 30, and other young stellar objects 2.

ACKNOWLEDGMENTS

We thank the referee, Tom Ray, for helpful comments and suggestions which improved the clarity of the paper. This work was performed as part of the Origin and Evolution of Stars and Galaxies Program of the Presidium of the Russian Academy of Sciences under support of INTAS grant no. 03-51-6311 and grant no. NSh-8542.2006.2.

REFERENCES

Anglada G., López R., Estalella R. et al. 2007, AJ, 133, 2799
Arce H. G., Shepherd D., Gueth F. et al. 2007, Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil (eds.), University of Arizona Press, Tucson, p.245
Artymowicz P., Lubow S. H., 1994, ApJ 421, 651
Bacciotti F., Eislöffel, J., Ray, T. P., 1999, A&A, 350, 917
Burrows C. J., Stapelfeldt K. R., Watson A.M. et al. 1996, 473, 437
Cotera, A. S., Schneider, G., Hines, D. C., Whitney, B. A., 2007, AJ, submitted
Ferreira J., Dougados C., Cabrit S., 2006, A&A 453, 785
Ferreira J., Zanni C., Mem.S.A.It., 78, 348
Grinin V.P., Tambovtseva L.V. 2002, Astron. Let., 28, 601
Grinin V.P., Tambovtseva L.V. 2006, Astrophysics, 49, 473
Grinin V.P., Tambovtseva L.V., Sotnikova N. Ya., 2004, Astron. Let., 30, 694
Gueth F., Guilloteau S. 1999 A&A, 343, 571
Hartigan P., Edwards S., Ghandour L., 1995, ApJ, 452, 736
Kwan J., Tademaru E., 1995, ApJ, 454, 382
Mundt R., Fried J.W., 1983, ApJ, 274, 83

Pety J., Gueth F., Guilloteau S., Dutrey A., 2006, A&A, 458, 841
Ray T.P., Mundt R., Dyson J.E. et al. 1996, ApJ, 468, L103
Stapelfeldt, K. R., Watson A. M., Krist, J. E., et al. 1999, ApJ Lett. 516, L95
Watson A. M., Stapelfeldt, K. R., 2004, ApJ 602, 860
Watson A. M., Stapelfeldt K. R., 2007, AJ 133, 845
Tambovtseva L. V., Grinin V.P., 2008, Astron. Lett. 34, 231, (astro-ph/0801.2236)
Wood, K., Wolk, S. J., Stanek, K. Z., Leussis, G., Stassun, K., Wolff, M., Whitney, B. 2000, ApJ Lett., 542, L21
Wood, K., Wolff, M. J., Bjorkman, J. E., Whitney, B. 2002, ApJ, 564, 887

2 Cotera et al. (2007) studying the images of the young stellar objects obtained with HST, found three other objects with the variable lateral asymmetries analogous to that detected in HH 30.