Wind Dynamics and Circumstellar Extinction Variations in the T Tauri Star RY Tau

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Abstract

The wind interaction with the dusty environment of the classical T Tauri star RY Tau has been investigated. During two seasons of 2013-2015 we carried out a spectroscopic and photometric (BVR) monitoring of the star. A correlation between the stellar brightness and the radial velocity of the wind determined from the Hα and Na D line profiles has been found for the first time. The irregular stellar brightness variations are shown to be caused by extinction in a dusty disk wind at a distance of about 0.2 AU from the star. We suppose, that variations of the circumstellar extinction results from cyclic rearrangements of the stellar magnetosphere and coronal mass ejections, which affect the dusty disk wind near the inner boundary of the circumstellar disk.

Introduction

Young low-mass (≤ 2 M⊙) stars with accretion disks are called classical T Tauri stars. The age of these stars is ~1 Myr. At this age, the planetary system is in the process of formation, the star is surrounded by a disk of gas and dust, and the accretion of disk material onto the star continues. T Tauri stars have a deep convective envelope and quite a strong surface magnetic field (~1 kG). The disk accretion of conducting material is stopped by the magnetic field at a distance of several stellar radii, and the gas streams are channeled along magnetic field lines onto the stellar surface. This is the so-called magnetospheric accretion (Camenzind 1990; Koenigl 1991; Bouvier et al. 2007). The observational evidence for magnetospheric accretion in T Tauri stars is well known: the Doppler shift of absorption lines formed in the infalling gas, and the hot spots on the stellar surface at the base of the accretion columns. The accretion rate ranges from 10^{-10} to 10^{-7} M⊙ yr^{-1} (Hartigan et al. 1995; Gullbring et al. 1998; White and Ghez 2001).

The radius of the boundary region between the accretion disk and stellar magnetosphere is approximately equal to the corotation radius (the distance from the star at which the angular velocity of the star is equal to the Keplerian angular velocity in the disk). For a solar-mass star rotating with a period of 7 days (the mean rotation period of T Tauri stars), the corotation radius is equal to five stellar radii. Although the accretion disk is composed of gas and dust, dust cannot be too close to the star. The inner radius of the dust disk is determined by the dust sublimation temperature. Most of the T Tauri stars are of spectral type K, and the inner radius of the dust disk is ~0.1 AU. Since hot dust radiates in the near infrared, the inner radii of the dust disks are measured by infrared interferometry (see, e.g., Akeson et al. 2005).

Apart from the accretion of matter, classical T Tauri stars exhibit an intense wind. Various types of wind are possible. The stellar wind (an analog of the solar one) flows along open magnetic field lines predominantly from polar regions (Matt and Pudrits 2005). The disk wind
flows from the disk surface. The disk has its own magnetic field; therefore, the magneto-
centrifugal effect, the acceleration of ionized gas along open magnetic field lines in the disk,
arises (Blandford and Payne 1982). Other types of wind can arise at the magnetosphere–disk
boundary: an X-wind (Shu et al. 1994) and a conical wind (Romanova et al. 2009). Below,
we will arbitrarily call this a “magnetospheric” wind. Episodic coronal mass ejections are also
possible (Ferreira et al. 2000). The difference between the profiles of emission lines forming
in the stellar and disk winds as well as their dependence on the inclination of the stellar
rotation axis were discussed by Kurosawa et al. (2011) and Grinin and Tambovtseva (2011).
The profiles of emission lines forming in the conical wind were considered by Kurosawa and
Romanova (2012).

Significantly, the accretion and wind processes are nonstationary, which affects the emission
line profiles. Periodic variations due to rotational modulation in the case of an axisymmetric
magnetic field are also occasionally observed (Petrov et al. 2001; Bouvier et al. 2003; Petrov et
al. 2011). The most dramatic phenomena occur at the base of themagnetospheric wind. The
difference in angular velocity between the star and the disk at its inner boundary causes the
magnetic loops connecting the star to the disk to be twisted, leading to an amplification of the
magnetic energy, the opening (inflation) of the magnetosphere, and the ejection of material in
the form of a wind, whereupon the magnetosphere is again restored. Such cyclic rearrangements
of the magnetosphere and mass ejections can occur quasiperiodically on a time scale of several
stellar rotations (Goodson et al. 1997; Romanova et al. 2009).

In this study, we are interested in the interaction of a nonstationary magnetospheric wind
with the dusty environment of the star. Large dust grains are concentrated in the disk plane,
but fine dust is present in the disk atmosphere and can be carried away by the disk wind
through the collisions of dust grains with neutral gas atoms (Safier 1993). The calculations of
the thermal balance of dust performed by Tambovtseva and Grinin (2008) showed the dust to
survive in the hot wind from young stars. If the line of sight to the star passes at a small angle
to the disk plane, then the dust attenuates appreciably the light from the star (circumstellar
extinction).

The disk wind lifting dust above the disk plane is more intense at the inner, hottest, disk
boundary. This creates a kind of a dust screen around the star. Magnetospheric wind variations
can exert some influence on this screen. In T Tauri stars, the distance from the magnetosphere-
disk boundary (near the corotation radius) to the inner boundary of the dust disk (dust sub-
limation radius) is relatively small: ≈0.1 AU. During mass ejections from the magnetosphere
with a velocity of 200 – 300 km s$^{-1}$, this distance is traversed in about one day. Consequently,
one might expect a correlation between the observed wind velocity and circumstellar extinction,
possibly, with some time delay.

To investigate the wind dynamics and the possible influence of the wind on circumstellar
extinction, we carried out a long series of spectroscopic and photometric observations for the
T Tauri star RY Tau. We chose this object for our observations, because the circumstellar disk
of RY Tau is inclined at an angle of 20° ± 5° degrees to the line of sight (Isella et al. 2010),
i.e., we see the star through the disk wind.

The main parameters of RY Tau (see Lopez-Martinez and Gomez de Castro 2014) are:
spectral type G1, bolometric luminosity $L = 9.6 \, L_{\odot}$, radius $R = 2.9 \, R_{\odot}$, and mass $M = 2
M_{\odot}$. On the log $T$ – log $L$ diagram (Siess et al. 2000), the star is on a radiative track at the
boundary between the T Tauri and Herbig Ae stars. The broad photospheric lines, $v \sin i \approx 50
km \, s^{-1}$, point to a rapid rotation of RY Tau. At this stellar radius and a high inclination of the
rotation axis, the rotation period of the star can be within the range 2.3 – 3.4 days.

The spectral energy distribution for the star in the range from 0.1 to 1000 µm corresponds
to the model of a disk of gas and dust with a mass of \( \approx 0.03 \, M_\odot \) (Robitaille et al. 2007). According to infrared interferometry (Akeson et al. 2005; Pott et al. 2010; Schegerer et al. 2008), the inner radius of the dust disk is \( R_{\text{in}} = 0.2 – 0.3 \) AU, depending on the disk model. A millimeter-band disk image shows that the inclination of the disk rotation axis to the line of sight is \( 65^\circ – 75^\circ \) (Isella et al. 2010). RY Tau can be classified by this parameter as belonging to UX Ori stars (Grinin et al. 1991).

RY Tau has an extended bipolar jet (St-Onge and Bastien 2008). The jet structure and kinematics were investigated by Coffey et al. (2015) and Agra-Amboage et al. (2009). X-ray emission from the jet of RY Tau was observed by Chandra (Skinner et al. 2011). In the optical range, RY Tau has an emission line spectrum typical of T Tauri stars. The variability of emission line profiles was investigated by Chou et al. (2013). RY Tau is one of the brightest T Tauri stars, and its photometric history has been well documented. The most detailed analysis of the photometry for RY Tau was performed by Zaitseva (2010) based on the data obtained from 1965 to 2000. Quasi-periodic variations that are probably associated with eclipses by dust clouds in the circumstellar disk were revealed. Periods of 7.5, 20, and 20.9 days manifested themselves in different years of observations. No stable period that could be identified with the rotation period of the star was detected. Continuous photometry for RY Tau during three weeks by the MOST satellite did not reveal a periodic signal either (Siwak et al. 2011).

Two noticeable brightenings, in 1983–1984 and 1996–1997, were observed against the background of irregular stellar brightness fluctuations in the range \( V = 9^{m}.5 – 11^{m}.5 \) (Herbst and Stine 1984; Herbst et al. 1994; Zaitseva et al. 1996). The color–magnitude diagram for RY Tau is typical of UX Ori stars. As the star fades, its \( B – V \) color index initially increases and then, at a deep minimum, decreases, though a large scatter of individual color indices is observed. The spectral characteristics of the star do not change with brightness. This suggests that circumstellar extinction variations are mainly responsible for the variability (Petrov et al. 1999).

**Observations**

The observations were carried out at the Crimean Astrophysical Observatory during two seasons from 2013 to 2015. The spectroscopic observations were carried out with the echelle spectrograph of the 2.5-m Shajn telescope using an iKON-L 936 (2048 x 2048 pixel) CCD camera. With a 2" entrance slit, the spectral resolution was \( \lambda/\Delta \lambda \approx 25000 \). The spectroscopic observations were performed in short series of four days to cover the rotation period of the star (about three days) and to reveal the possible rotational modulation of emission lines. Because of the weather conditions, these series were sometimes shorter. As a rule, several 30-min spectral exposures were taken over the night, which were then summed. The mid-exposure times of observations are given in Table 1. In total, we observed the star for 32 nights: 12 and 20 nights in the 2013–2014 and 2014–2015 seasons, respectively.

The photometric observations of RY Tau were carried out at the 1.25-m AZT-11 telescope using two detectors: (1) an FLI ProLine PL230 (2048 x 2048 pixel) CCD camera with a 10.9 x 10.9 field of view and an angular resolution of 0.32/pixel and (2) a Finnish five-channel pulse-counting photometer–polarimeter. The observations were performed in Johnson’s \( BVR \) bands. The root-mean-square error of each measurement was, on average, \( 0^{m}.005 \) and \( 0^{m}.01 \) for the photoelectric and CCD observations, respectively. The results are presented in Table 1. In most cases, the times of our photometric observations coincided with the mean times of spectral exposures within about one hour. Given that the brightness of RY Tau changes, on average, by \( 0^{m}.1–0^{m}.2 \) in one day, the error of the magnitudes listed in Table 1 at the time
of our spectroscopic observations can reach $0.01$. When we failed to perform photometry simultaneously with spectroscopy, we determined the stellar brightness at the time of our spectroscopic observations by interpolation between adjacent dates, and the errors could reach $0.1$. These errors are given in Table 1.

Table 1: Times of observations, stellar brightness, equivalent width of Hα emission and radial velocity of outflow.

| JD  | V   | σ   | EW  | σ   | RV$_{max}$ | σ   |
|-----|-----|-----|-----|-----|------------|-----|
| 2450000+ | m  | m  | Å   | Å   | km/s       | km/s |
| 6592.500 | 10.46 | 0.01 | 18.3 | 1.0 | -146       | 10   |
| 6593.437 | 10.70 | 0.01 | 19.3 | 1.0 | -137       | 8    |
| 6594.371 | 10.45 | 0.01 | 11.5 | 0.5 | -130       | 7    |
| 6595.347 | 10.38 | 0.01 | 9.7  | 0.5 | -130       | 6    |
| 6605.535 | 10.09 | 0.01 | 7.1  | 1.5 | -185       | 6    |
| 6606.442 | 10.11 | 0.01 | 7.2  | 1.5 | -225       | 12   |
| 6621.312 | 10.19 | 0.01 | 6.5  | 0.5 | -240       | 10   |
| 6691.387 | 9.80  | 0.05 | 8.1  | 0.5 | -232       | 6    |
| 6742.226 | 10.65 | 0.10 | 11.2 | 1.5 | -155       | 10   |
| 6743.187 | 10.70 | 0.10 | 12.9 | 2.0 | -175       | 5    |
| 6744.244 | 10.73 | 0.10 | 17.3 | 0.2 | -163       | 10   |
| 6748.294 | 10.97 | 0.10 | 21.4 | 1.5 | -160       | 10   |
| 6905.524 | 10.30 | 0.01 | 7.1  | 1.0 | -186       | 15   |
| 6906.520 | 10.26 | 0.01 | 11.0 | 1.0 | -220       | 10   |
| 6907.503 | 10.30 | 0.05 | 8.5  | 0.4 | -220       | 6    |
| 6908.508 | 10.35 | 0.01 | 9.4  | 0.3 | -196       | 8    |
| 6933.554 | 10.13 | 0.05 | 14.0 | 1.0 | -275       | 12   |
| 6934.485 | 10.10 | 0.05 | 8.8  | 0.3 | -275       | 12   |
| 6935.493 | 10.12 | 0.01 | 14.5 | 0.3 | -185       | 10   |
| 6936.499 | 10.17 | 0.01 | 11.2 | 0.3 | -196       | 8    |
| 6964.459 | 10.32 | 0.01 | 6.7  | 0.3 | -170       | 8    |
| 6975.437 | 10.42 | 0.01 | 16.2 | 0.5 | -209       | 6    |
| 6976.447 | 10.59 | 0.01 | 19.9 | 0.5 | -199       | 6    |
| 6977.462 | 10.60 | 0.05 | 15.0 | 0.5 | -200       | 10   |
| 6993.257 | 10.27 | 0.01 | 21.9 | 0.5 | -214       | 10   |
| 7058.219 | 10.62 | 0.01 | 22.0 | 0.5 | -173       | 15   |
| 7059.273 | 10.73 | 0.05 | 9.7  | 0.4 | -182       | 10   |
| 7060.238 | 10.80 | 0.10 | 12.2 | 0.5 | -176       | 15   |
| 7089.284 | 11.09 | 0.01 | 15.6 | 0.5 | -134       | 7    |
| 7090.245 | 11.18 | 0.01 | 17.6 | 0.5 | -134       | 7    |
| 7091.269 | 11.16 | 0.01 | 18.8 | 0.3 | -120       | 8    |
| 7092.267 | 11.15 | 0.01 | 15.7 | 0.5 | -125       | 8    |
Results

Over the time of our observations, the brightness of RY Tau varied within the range from $V = 9^{m}.8$ to $V = 11^{m}.2$ without any noticeable dependence of the colors on brightness. Fig. 1 presents the light curve of RY Tau and the times of our spectroscopic observations.

Figure 1: Light curve of RY Tau in the 2013—2014 and 2014—2015 seasons. The vertical dashes mark the times of our spectroscopic observations.

In this paper, we use the H$\alpha$ and Na D line profiles as indicators of gas flows – the wind and accretion. The typical H$\alpha$ line profile consists of a broad emission with symmetric wings extended to $\pm 300$ km s$^{-1}$ and a blueshifted absorption indicating an outflow of matter. According to the classification of Reipurth et al. (1996), this is a type II B profile. This type of profile is characteristic of a disk wind when the line of sight passes at a small angle to the disk surface (Grinin and Tambovtseva 2011; Kurosawa et al. 2011). If, however, the star is seen pole-on, then the line of sight passes through the stellar wind regions and a P Cyg (type IV B) profile is observed. Fig. 2 presents a sample of several H$\alpha$ line profiles in the spectrum of RY Tau. What is unusual is that both types of profile with a gradual transition from type II
B to type IV B are observed. Obviously, this is due to a change in wind geometry rather than a change in inclination. A P Cyg profile suggests a radial outflow with acceleration, which is probably related to some temporary gas ejection episodes.

In addition, a dip in the red line wing, occasionally fairly deep but not lower than the continuum, often appears in the Hα profile. Concurrently, an additional absorption appears in the Na D profile on the red side, indicating the infall of gas to the star with a radial velocity up to +200 km s\(^{-1}\). Signatures of both outflow and accretion (type II B + II R) are often observed simultaneously in the profiles of these lines.

Figure 3: Correlated variations in the Hα (top) and Na D (bottom) profiles. The photospheric profile of the star 35 Leo (G1.5 IV-V) rotationally broadened to \(v \sin i = 50\) km s\(^{-1}\) (dashed line) is superimposed on the Na D profile.

The Hα and Na D profiles are compared in Fig. 3. It can be seen that the additional (to the photospheric profile) absorption in the Na D lines corresponds to the absorption dips in the blue or red Hα wing. The radial velocity of the wind can be measured from the blue edge of the absorption in the Na D lines, but the noise at the continuum level does not always allow this edge to be determined. In those cases where this was possible, we measured the radial velocity of the wind from the Na D2 line and from the blue edge of the absorption in the Hα line indicated by the vertical dashes in Fig. 3. The result is shown in Fig. 4. A clear correlation between the velocities measured by the two methods confirms our assumption that the dips in the Hα wing are actually absorptions. The radial velocity of the wind measured in all spectra from the Hα line is given in Table 1. The three most characteristic types of Hα profile that alternate or pass into one another can be identified (Fig. 5). They can be arbitrarily designated as “wind and accretion” (II B + II R), “disk wind” (II B), and “fast wind” (IV B or P Cyg). Out of the 32 observing nights, the “disk wind” (14 nights) and “wind and accretion” (11 night) were observed most frequently.

How fast do the line profiles change? Fig. 5 shows examples of several short series of spectra,
Figure 4: Comparison of radial velocities of wind measured from the H\(\alpha\) and Na D2 profiles.

Figure 5: Series of spectra showing three types of H\(\alpha\) profiles. The left panel presents the profiles with signatures of wind and accretion. The dates at which the spectra were taken, from top to bottom: March 7, 8, 9, and 10, 2015. The middle panel presents the profiles typical of a disk wind (March 25, 26, 27, and 31, 2014). The right panel presents the series of spectra including the “fast wind” episode (October 2, 3, 4, and 5, 2014).

each taken on 4–6 consecutive nights. The profile may not change for four days, i.e., there is no rotational modulation, the type of profile does not depend on which side of the star we see. Both the appearance and disappearance of the “fast wind” (P Cyg profile) occur rapidly, in one day. Out of the 32 observing nights, P Cyg profiles were observed in seven cases. This means that at an average duration of the continuous series of about three consecutive nights, the probability of detecting a P Cyg profile is about 0.2. Consequently, it can be assumed that, on average, such a profile appeared approximately once in 15 days, i.e., once in several stellar rotations.

The main result of our observations is the detection of a correlation between the stellar brightness and the radial velocity of the wind (Fig. 6). The same correlation is shown in Fig. 7 as a gray-scale map. The entire brightness range was divided into 0\(^m\).2 bins, and the spectra corresponding to each brightness bin were averaged.
Figure 6: Correlation between the stellar brightness $V$ and the radial velocity of the wind $RV$.

Figure 7: Gray-scale map of $H\alpha$ profiles at various stellar brightness levels. The white and black areas correspond to the maximum and minimum intensities in the $H\alpha$ profile.

The rates of change of the stellar brightness $V$ and the radial velocity of the wind $RV$ can be characterized as follows. The brightness changes in one day by $0^m.1$–$0^m.2$ in most cases and by as much as $0^m.45$ in rare cases. The radial velocity of the wind changes in one day by $10$–$40$ km s$^{-1}$ in most cases and by $90$ km s$^{-1}$ in rare cases. The entire amplitude of the brightness and velocity variations shown in Fig. 6 refers to long time intervals: about one month. As has been pointed out above, previous studies have shown that the brightness variations in RY Tau are caused mainly by circumstellar extinction variations. Our observations also confirm this conclusion. If the $V$ brightness of the star changed due to accretion, i.e., the appearance of hot spots on the stellar surface, then the depth of photospheric lines in the range 5000–6000 Å
should have changed because of the veiling effect. As the brightness changes by one magnitude, the line depth must decrease accordingly by a factor of 2.5. However, our observations show that this effect is completely absent. At a difference in stellar brightness by 1\text{m}, the depth of photospheric lines does not change within the measurement accuracy, ±2% of the continuum level. Consequently, the brightness variations in the visible spectral range are caused mainly by the obscuration of the star by dust.

From the variations in the equivalent widths of emission lines, we can conclude how vast the region eclipsed by the dust screen is. In Fig. 8, the equivalent widths of the H\textalpha emission line and the [OI] 6300 Å emission are plotted against the stellar brightness. The H\textalpha emission is formed in the immediate vicinity of the star, in the magnetosphere and the wind (Kurosawa et al. 2011), as well as on the stellar surface at the base of the accretion columns (Dodin 2015). The [OI] 6300 Å emission line peak in the spectrum of RY Tau is at a radial velocity of about -9 km s\textsuperscript{-1} relative to the star. This line is formed in the rarefied gas of a collimated wind (jet). The equivalent width of the [OI] emission was measured in the range from -30 to +30 km s\textsuperscript{-1} relative to the peak. The [OI] emission originating in the Earth’s atmosphere is usually shifted due to the velocity difference and does not affect these measurements. In the case where only the stellar photosphere is screened, the emission line fluxes remain constant. In this case, the emission line equivalent width will increase with decreasing brightness as is indicated by the dashed line in Fig. 8. Our observations show that the equivalent width of both emission lines actually increases with decreasing stellar brightness. This means that the emission region is obscured incompletely by dust. In addition, a significant intrinsic variability in the lines is observed. In particular, the range of variations in the [OI] 6300 Å line is noticeably greater than might be expected when the brightness changes by one magnitude. The formation region of this line closest to the star probably also responds to changes in the magnetosphere: the line intensity decreases when a "fast wind" appears.

Discussion

In this paper, we investigate the dynamics of the stellar wind from RY Tau. The blueshifted absorption in the H\textalpha and Na D line profiles is supposed to be an indicator of the wind flows. It should be mentioned, that an alternative interpretation of the H\textalpha line profiles was proposed by Grinin and Tambovtseva (1995) when studying the variability of emission line profiles in
Herbig Ae/Be stars: if a dust cloud obscuring successively different parts of the emission region from the observer moves around the star, then characteristic changes must be observed in the \( \text{H}\alpha \) line profile. However, the views of the causes of spectroscopic and photometric variability of T Tauri stars have changed noticeably over the elapsed 20 years. Great progress has been achieved in studying the interaction of the stellar magnetic field with the accretion disk and the formation of a wind and accretion flows. In particular, these processes were shown to be essentially nonstationary on a time scale of several stellar rotations (for a review, see Romanova et al. 2014). This inevitably affects the observed emission line profiles. There is good reason to believe that the variability of emission lines in the spectra of classical T Tauri stars reflects the actual dynamical processes and is not caused only by eclipses. For example, fast irregular variability of the Balmer lines, including the episodic appearances of P Cyg profiles indicating active mass ejections, has been repeatedly observed in the T Tauri star SU Aur, which in many ways resembles RY Tau (Jones and Basri 1995).

Cyclic rearrangements of the magnetosphere accompanied by coronal mass ejections can in principle explain the observed variability in the \( \text{H}\alpha \) profile, where the "quiescent wind" is occasionally disrupted by "fast wind" episodes. A similar effect is observed in the star AA Tau, which is also oriented nearly equator-on (Bouvier et al. 2003). The synchronous changes in the radial velocity of the wind and accretion flows were interpreted in terms of the model of a dynamical rearrangement of the magnetosphere. During the magnetospheric inflation, the slope of the magnetic field lines in the inner disk changes and, accordingly, the radial velocity of the gas moving along the field lines changes. For AA Tau, the observed brightness variations are periodic. It was interpreted as recurrent occultation of the star by the warped inner disk due to the inclined magnetosphere (Bouvier et al. 1999).

In contrast to AA Tau, RY Tau shows no rotational modulation either in the brightness variations or in the emission line intensity or profile variations. Since there is no veiling of the photospheric spectrum in the visible spectral range, one can hardly expect any photometric variability caused by nonstationary accretion. The magnetosphere of RY Tau is probably inclined only slightly to the rotation axis and is axially more symmetric than that in other T Tauri stars; therefore, we have a rare opportunity to investigate the dynamical phenomena in the magnetosphere and the wind undistorted by rotational modulation. In RY Tau, we observe a new effect, the wind interaction with the dusty environment of the star. The correlation between the wind velocity and circumstellar extinction suggests that the distance from the "fast wind" formation region to the dust screen region is small, 0.1–0.2 AU, i.e., the dust screen is at the inner rim of the dust disk. In other words, the irregular photometric variability of RY Tau is governed not by random eclipses by dust clouds in the accretion disk atmosphere but by MHD processes in the stellar magnetosphere. Presumably, the magnetospheric inflation and the succeeding gas ejection temporarily destroy the dust screen at the inner disk boundary. After the restoration of the magnetosphere, the disk wind again lifts dust and restores the dust screen.

Amplitude of light variability, caused by extinction due to dust in the disk wind of RY Tau, is \( \sim 1^m \). The mass of the dust causing such extinction can be estimated. To attenuate the light from the star by one magnitude, the number of dust particles on the line of sight in a column with a cross section of 1 cm\(^2\) must be, in order of magnitude \( \approx 1/(\pi \cdot a^2) \), where \( a \) - radius of a particle. Then, the dust column density is \( m_{\text{col}} \approx 4/3 \cdot a \cdot \rho \), where \( \rho \) is average density (g/cm\(^3\)). In projection onto a star of radius \( R_* \) the mass of the dust particles is \( m_{\text{col}} \cdot \pi \cdot R_*^2 \). At an inner radius of the dusty disk \( R_{\text{in}} \), the mass of dust in a ring zone around the star of height \( 2 \cdot R_* \) and the length of \( 2 \cdot \pi \cdot R_{\text{in}} \), is \( 4 \cdot (R_{\text{in}}/R_*) \cdot m_{\text{col}} \cdot \pi \cdot R_*^2 \).

At a tangential (across the line of sight) velocity \( V_t \), the dusty wind travels a distance equal
to the diameter of the star, in the time \( t = 2R_\ast/V_t \). Consequently, the dust mass flux is

\[
\dot{M}_{\text{dust}} \approx 4 \cdot \left( \frac{R_{\text{in}}}{R_\ast} \right) \cdot m_{\text{col}} \cdot \pi \cdot R_\ast^2/t,
\]

or

\[
\dot{M}_{\text{dust}} \approx 8 \cdot R_{\text{in}} \cdot a \cdot \rho \cdot V_t.
\]

Assuming, as an example, \( a = 0.3 \) \( \mu \)m, \( \rho = 2 \) g/cm\(^3\), \( R_{\text{in}} = 0.2 \) AU and \( V_t = 100 \) km/s, we obtain \( \dot{M}_{\text{dust}} \approx 2 \cdot 10^{-11} \) \( M_\odot/\)yr. At the dust to gas mass ratio 0.01, the mass loss rate in the wind is \( \dot{M}_{\text{wind}} \approx 2 \cdot 10^{-9} \) \( M_\odot/\)yr.

Some uncertainty in this estimate may stem from the fact that we do not know the direction of the disk wind velocity vector. Only the radial velocity of the wind is determined from observations. For comparison, the most reliable value of the accretion rate onto RY Tau derived from the veiling level in the ultraviolet spectral range is \( \dot{M}_{\text{accretion}} = (6–9) \cdot 10^{-8} \) \( M_\odot \) yr\(^{-1}\) (Calvet et al. 2004), i.e., an order of magnitude higher than the outflow rate \( \dot{M}_{\text{wind}} \).

The variability of young stars due to circumstellar extinction shows itself most clearly in UX Ori stars, which are more massive and hotter than T Tauri stars. Since the inner boundary of the dust disk is farther from the star (about 0.5 AU), one might expect the correlation between the wind and circumstellar extinction in such stars to be not so obvious. In T Tauri stars, the boundary of the dust disk is closer to the region from where the ”magnetospheric” wind starts; therefore, these effects are more pronounced.

The variability mechanism considered here concerns the short-term brightness variations on a time scale of several stellar rotations. The longer-term dimming events can be caused by a nonuniform distribution of dust in the accretion disk. In course of disk accretion, local concentrations of dust arrive gradually at the inner boundary of the disk, from where the dust gets into the wind and causes a deep and long-lasting event of extinction. Such an effect was observed in the T Tauri star RW Aur A. During a deep dimming of the star in the optical range, its near-infrared (2–5 \( \mu \)m) brightness rose. This was interpreted as a manifestation of hot dust in the wind directed toward the observer (Shenavrin et al. 2015).

**Conclusion**

The photometric variability of RY Tau is attributable to circumstellar extinction variations. The dust screen responsible for the stellar variability lies at the inner boundary of the dust disk at a distance of about 0.2 AU from the star. The radial velocity of the wind is, on average, \( \sim 100 \) km s\(^{-1}\), but gas ejections a higher velocity, up to 280 km s\(^{-1}\), are occasionally observed. A clear correlation between the radial velocity of the wind and the stellar brightness has been found for the first time. We assume that the circumstellar extinction variations result from a cyclic rearrangement of the stellar magnetosphere and coronal mass ejections, which affects the dusty disk wind near the inner boundary of the disk.

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