Outflows and Accretion on the Late Phases of PMS Evolution. The Case of RZ Psc

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We consider the spectral variability of the post T Tauri star RZ Psc. The star does not show clear accretion traces, but at the same time it has distinct variable blue-shifted features in the Na I D resonance doublet and lines of other alkali metals which indicate the matter outflow from the stellar vicinity. We suppose that in case of RZ Psc we deal with the special type of interaction between the remnants of accreting gas and stellar magnetosphere in the “magnetic propeller” regime. It is expected that accretion in the propeller regime exists in some others young stars.

1 Introduction

Over three recent decades the magnetospheric accretion paradigm was developed and improved to explain the observed activity among young solar type stars. These so-called T Tauri stars actively accrete the matter from their protoplanetary disks and possess the notable spectroscopic evidences for complex gas motion in the near vicinity of the star. The profiles of the strong hydrogen emission lines and lines of some metals reveal the accretion infall as well as the less significant matter outflow due to the magnetospheric conical and X-wind. The overview of the basic concepts of the theory and its application to the observations can be found in the review by Bouvier et al. [1].

According to the recent investigations of several open clusters and young stellar associations, the phase of the actively accreting T Tauri star lasts only few million years (Myr) (see, e.g., the review by Williams and Chieza [2]). During this period the circumstellar disk evolves from an optically thick gaseous and dusty protoplanetary disk into an optically thin debris disk consisting of large particles, planetesimals, and planets. From the observational point of view, this evolution is reflected by a difference between the “Classical” (CTTS), “Weak line” (WTTS), and “Post” T Tauri stars. The last two subclasses in this sequence possess the mild characteristics of activity which decay with their age. Fedele et al. [3] show that on the timescale of 10 Myr accretion becomes vanishingly small (less than

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$10^{-11} M_\odot$ yr^{-1}). Hence, the spectroscopic traces of the accretion/outflow process should also disappear on such a timescale.

The careful investigation of the stars near or even above this limit has the crucial importance for our understanding of the late stages of Pre-Main Sequence evolution. In the systems with the low accretion rate some special cases of interaction between stellar magnetosphere and remnants of the accreting gas can arise and can be studied in its "pure form". Such observational traces are not masked by the more prominent accretion features typical of early stages of the PMS evolution.

One of such unique objects is the star RZ Psc.

2 RZ Psc and its spectroscopic behavior

RZ Psc belongs to the family of young variable UX Ori type stars. The photometric and polarimetric activity of these stars is caused by the variable circumstellar (CS) extinction [4]. RZ Psc is one of the coolest (Sp = K0 IV) and eldest member of the family. According to the latest estimates, based on calculating the trajectory of the star in the gravitational potential of Galaxy, its age is about 25±5 million years [5, 6]. This value is considerably higher than the characteristic lifetime of the accretion disks and means that the star is surrounded by the significantly evolved accretion disk.

The spectrum of the RZ Psc strongly resembles the spectrum of a star that already passed the stage of the T Tauri stars, without any prominent emission features above the continuum level. There is the only important exception: the lines of the resonance sodium doublet Na I D show the blue-shifted absorption components which manifest the gas motion from the star toward the observer [7]. These absorption details were initially discovered in the spectra obtained in

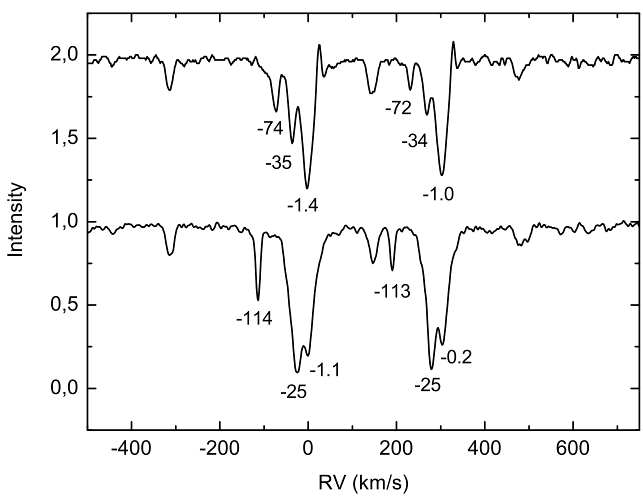

Figure 1: The Na I D lines in the spectra of RZ Psc observed with NOT.

the Peak Terskol Observatory during the seasons 2009–2012 with the moderate spectral resolution $R \sim 13500$ [7]. It should be stressed that despite blue-shifted absorptions are highly variable, no red-shifted details or signs of emission in Na D lines has been observed.

These details are very notable on the pair of the high-resolution FIES spectra ($R \sim 46000$), obtained in August and November 2013 by I. Ilyin with 2.56 m Nordic Optical Telescope (see [9] and Fig. 1).

The subsequent observations were carried out by one of the authors of our paper (D.E.M.) at the 2.4 m telescope of the Thai National Observatory with MRES echelle spectrograph in December 2014. The covered region was from 4400 to 8800 Å that allowed us to include lines of other alkali metals K I and Ca II into consideration. These lines are presented in Fig. 2.

One can see an appearance of the variable blue-shifted absorption components in Na I D lines which are accompanied by the similar structures in the K I 7699 Å line. The features in the K I line are less prominent due to the lower potassium abundance, but reach their maximum when the sodium lines also show the strongest additional absorption. The Ca II 8542 Å line belongs to the calcium IR triplet and demonstrates more complicated picture. The line core is filled in by the variable emission, while the additional low-velocity absorption appears on several dates. Nevertheless, RZ Psc still does not possess any clear accretion signs in its spectra.

The possible key to this mystery came from observations of the Hα line. It also has the pure absorption profile in RZ Psc spectrum. But a careful comparison of it with the synthetic profile and profile observed in the spectrum of the standard star σ Dra (K0 V) reveals the presence of the weak variable emission component in the central part of the Hα line. The spectral subtraction technique shows the narrow emission peak, that can be probably attributed to the chromospheric activity, and the broad (up to $\pm$ 200 km s^{-1}) emission base forms in the accreting matter (Fig. 3).

3 Discussion and conclusions

Measurement of the equivalent width (EW) of the Hα emission in RZ Psc spectra gives the mean value of about 0.5 Å. This value is significantly less than the standard value of 10 Å which separates the actively accreting CTTS from WTTS. According to this criteria, we can call RZ Psc as "the very Weak line T Tauri star". Measurement of Hα emission EW allows us to estimate the accretion rate in the system, using the empirical relationship between the observed emission line luminosity and total accretion luminosity from [8]. The obtained value $\dot{M} \sim 7 \times 10^{-12} M_\odot\,\mathrm{yr}^{-1}$ is an upper limit of the real accretion rate, because the Hα line in the RZ Psc spectrum possibly arises not only in the accreting matter but also in the stellar chromosphere. Nevertheless, this accretion rate is the lowest one known from the literature.

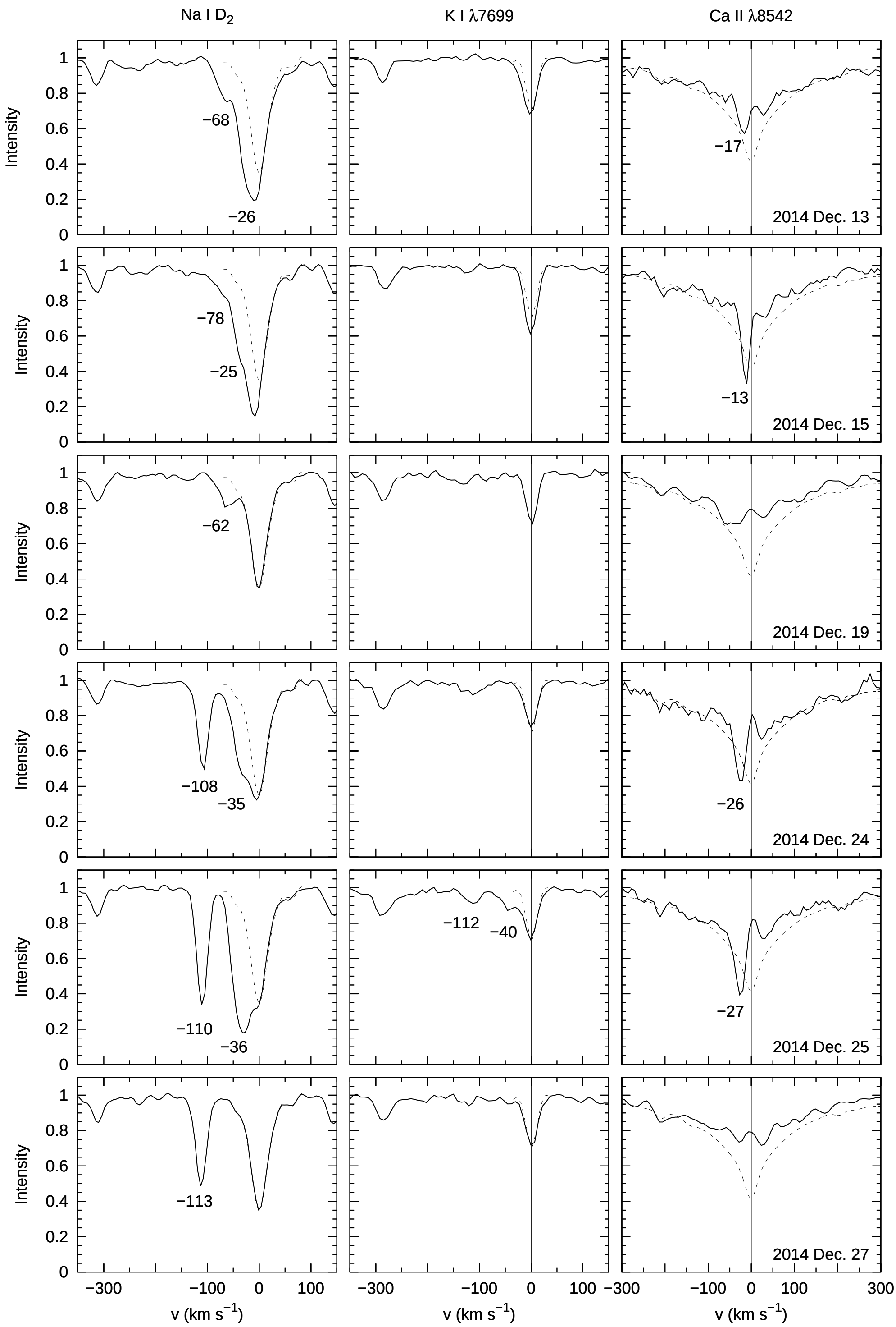

Figure 2: Alkali metal lines observed in the RZ Psc spectra with the MRES. The velocities in km s^{-1} of the variable absorption components are labeled. The reference photospheric profiles are plotted by dashed line.

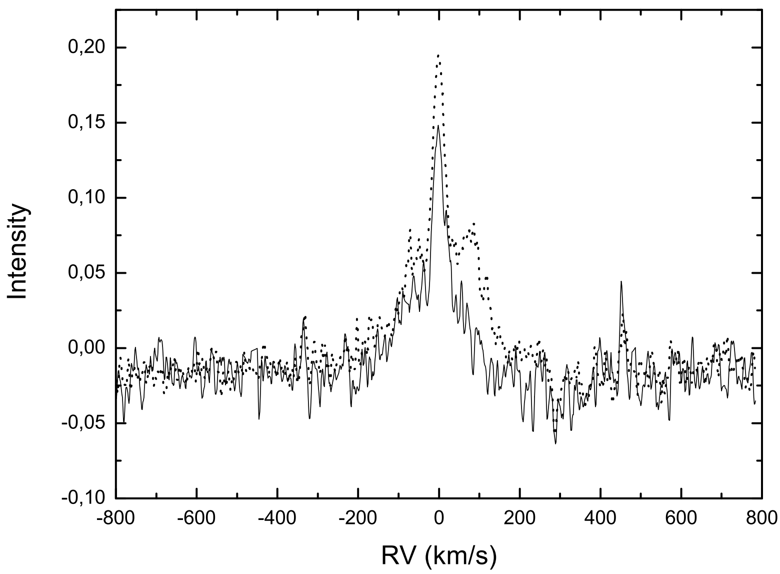

Figure 3: The emission components of the Hα line obtained after subtraction of the synthetic profile from the observed ones. Solid line corresponds to the observations obtained on Aug. 19, 2013, while the dotted line shows spectrum obtained on Nov. 21, 2013.

Hence, in the case of RZ Psc, we deal with the extremely low accretion rate and, at the same time, with nontrivial spectroscopic signs of the matter outflow. We supposed that the gaseous outflow from the RZ Psc vicinity was a result of the action of the so-called "propeller mechanism" arising at the interaction between the stellar magnetosphere and remnants of the gas in the circumstellar disk [9]. This mechanism is realized when the angular velocity of the star (and the magnetosphere) exceeds the angular velocity of the Keplerian disk at the truncation radius in the region where the magnetic field still controls the motion of the gas. The ratio between the corotation and truncation radii depends inversely on the mass accretion rate. When it is small, the truncation radius can significantly exceed the corotation radius. Under this conditions, most of the accreting matter is scattered into the surrounding space.

There are observational evidences (so-called AA Tau effect) that the situation, when the axis of magnetic dipole does not coincide with the rotational axis of the star, is not rare among young T Tauri stars (see, e.g., [10, 11]). Numerical simulations by Romanova et al. [12] showed that interaction between the accreting gas and inclined magnetic dipole produced the special case of a biconical outflow consisted of two expanding spiral structure. The multiple intersection of the line of sight by the spiral can produce the corresponding absorption lines shifted relatively to the star velocity.

Similar narrow absorption details are observed in the NaI D lines in the spectra of some other young stars such as MWC 480, NY Ori and BBW 76. However, these objects are at earlier evolutionary stages and show spectroscopic signs of accretion. However, the magnetic propeller regime is not necessary phase of the evolution of T Tauri stars. The unstable behavior of the gaseous outflow significantly complicates the theoretical modeling. Sobolev's theory for the medium with large velocity gradients was developed and applied to the media where the gas density was determined from the continuity equation. In the case of RZ Psc, the situation is quite different: narrow absorption components in the lines of the sodium doublet in combination with the lack of the emission in these lines indicate that the absorbing gas fills in only the minor part of the whole solid angle 4π (see [9]). It is important to learn how to calculate the profiles and intensities of the spectral lines formed in such conditions.

A more detailed description and discussion of the spectral variability of RZ Psc will be forthcoming.

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