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The evolutionary status of the UX Orionis star RZ Piscium

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ABSTRACT

The star RZ Psc is one of the most enigmatic members of the UX Ori star family. It shows all properties that are typical for these stars (the light variability, high linear polarization in deep minima, the blueing effect) except for one: it lacks any signatures of youth. With the lithium line 6708 Å as a rough estimate for the stellar age, we show that the "lithium" age of RZ Psc lies between the age of stars in the Pleiades (∼70 Myr) and the Orion (∼10 Myr) clusters. We also roughly estimated the age of RZ Psc based on the proper motion of the star using the Tycho-2 catalog. We found that the star has escaped from its assumed birthplace near to the Galactic plane about 30-40 Myr ago. We conclude that RZ Psc is a post-UXOr star, and its sporadic eclipses are caused by material from the debris disk.

Key words. RZ Psc – post UX Ori star – variability mechanism – young debris disk

1. Introduction

The star RZ Psc (Sp = K0 IV, Herbig (1960) is one of the most unusual variable stars. According to the properties of its light curve, it belongs to the family of young stars of the UX Ori type, the photometric and polarimetric activity of which is caused by the variable circumstellar (CS) extinction (Grinin et al. (1991)) According to the current models (Dullemond et al. (2003)), the region of the CS disk close to the dust evaporation zone, where the main part of the near infrared excess is formed (Natta et al. (2001)), is responsible for this variability. However, RZ Psc shows none of the classical signs of youth: it has neither infrared (JHK) excess (Glass, & Penston (1974))[1], nor emission in the H_α line (Kaminskii, Kovalchuk & Pugach (2000)). The star lies at the Galactic latitude $b \simeq -35°$, where there are neither young stars, nor star-formation regions. The brightness minima of RZ Psc are also quite unusual: with large amplitudes (up to $\Delta V \approx 2.5$ mag.), they are very brief (1-2 days; Zaitseva (1985), Kardopolov, Sahanionok & Shutemova (1980), Pugach (1981), Wenzel (1989)). Similar minima are sometimes also observed in another UXOrs but, in the case of RZ Psc, they are typical. Several attempts were undertaken to find the period between the star eclipses, but all were unsuccessful (Wenzel (1989)).

The above combination of the conflicting observational properties poses many questions about the evolutionary status of RZ Psc and the origin of the eclipses. To clarify these questions, we analyze the Li 6708 Å spectral line, which is commonly used for age estimations of solar-type stars (see e.g., Soderblom et al. (1993); Sestito & Randich (2005); da Silva et al. (2009)). In addition, we use the proper motion of RZ Psc from the Tycho-2 Catalog by Hog et al. (2000) to roughly estimate the time at which the star escaped from its birthplace near to the Galactic plane. Both estimates allow us to classify RZ Psc as a post-UXOr.

[1] RZ Psc is absent in the IRAS and Spitzer data bases.

2. The "lithium" age of RZ Psc

Although RZ Psc has already been investigated for a long time, most papers have been devoted to the study of its variability. There is only one paper (Kaminskii et al. 2000) in which the quantitative analysis of the star spectrum has been made. In that paper, however, there is no information about the Li 6708 Å line. To study this line, the spectrum of RZ Psc was obtained at the Terskol Observatory (Russia). The observations were made on 2009 Nov. 9, with the echelle spectrograph SPECPHOT (spectral resolving power R = 13500) at the 2 m telescope. The spectrum was reduced with the software package DECH by Galazutdinov (1992), which provides all standard tasks of CCD image and spectra processing. The wavelength calibration was made with an Fe-Ar comparison lamp spectrum.

A portion of the reduced spectrum around the Li 6708 Å line is displayed in Fig. 1. One can see that this line is present in the spectrum of RZ Psc and has a moderate depth, with an equivalent width of $EW(\mathrm{Li}) = 0.202 \pm 0.010$ Å. For comparison, in Fig. 1 we show two versions of a synthetic spectrum calculated for the same spectral range with the numerical code from Piskunov (1992)) and the VALD data base by Piskunov et al. (1995), Kupka et al. (1999). The spectra were broadened by rotation with $v \sin i = 23$ km/s (Kaminskii et al. 2000). In both cases we used the Kurucz (1979) model of atmosphere with $T_{ef} = 5250$ K, $\log g = 4.0$, and $v_{turb} = 2$ km/s. In one of these spectra, the Li abundance is the same as in the Sun. In the other one, it is 100 times higher. We see that in the first case, the

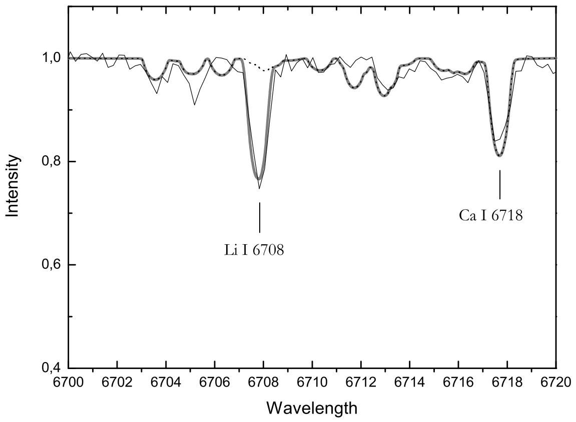

Fig. 1. The spectrum of RZ Psc around the Li 6708 Å line (thin line). The synthetic spectra with the Li excess (100 times larger than the solar abundance) (thick gray line) and without excess (dashed line) are shown (see text for details).

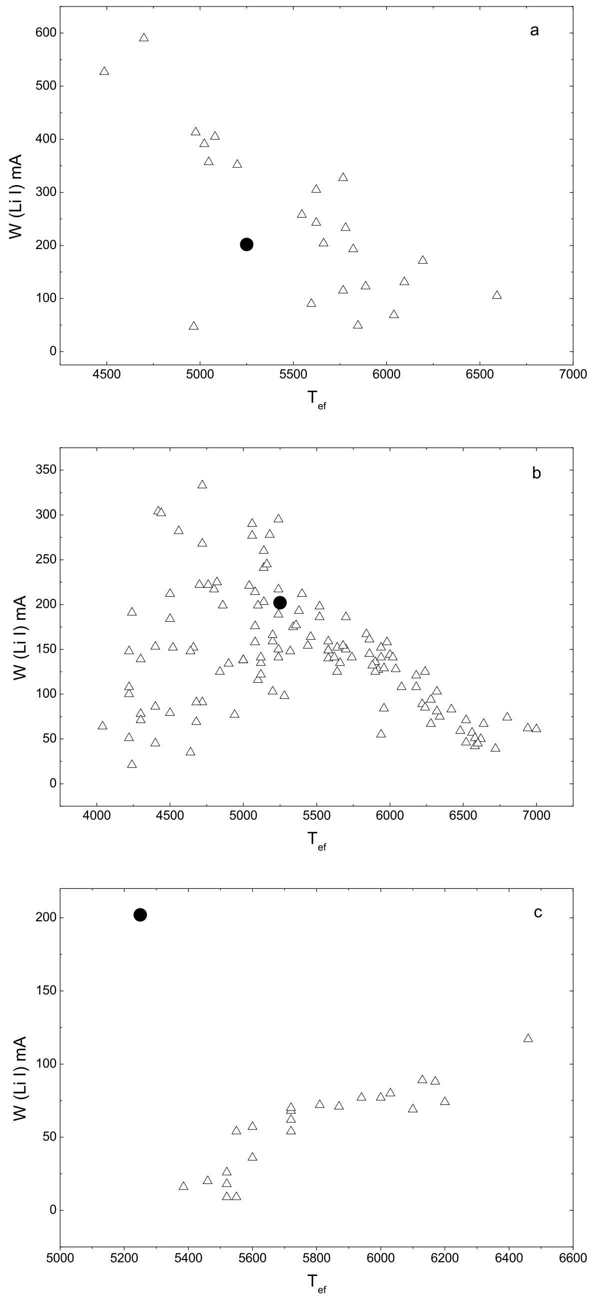

Fig. 2. Comparison of EW (Li, 6708 Å) in the spectrum of RZ Psc (circle) with the data for the stars in the clusters of different age (triangles): Orion (10 Myr) from King (1993); Pleiades (70 Myr) and Hyades (600 Myr) from Soderblom et al. (1990; 1993).

Li 6708 Å line is practically invisible. In the second case, the lithium line in the synthetic spectrum almost coincides with the observed one. Taking into account the possible uncertainties in the estimation of the spectral type of the star, we have calculated several additional synthetic spectra, changing the model parameters in the ranges $T_{ef} = \pm$ 250 K and $\log g = \pm$ 0.5, and these calculations confirmed the result obtained above.

Thus, the spectral analysis shows that the atmosphere of RZ Psc has a huge excess of lithium (about 100 times the solar abundance) and, according to this criterion, RZ Psc is not yet a main sequence star. The considerably high (for this spectral type) value of $v \sin i$ agrees with this conclusion (see the discussion by Bouvier (2008)). On the other hand, in the atmospheres of young solar-type stars (T Tauri stars) the excess of lithium is usually much greater than in our case (see Fig. 2a). For example, V718 Per (about the same spectral type as RZ Psc) has a lithium excess equals to about 3.2-3.5 dex (Grinin et al. (2008)), which is indicative of a primordial Li abundance (Pavlenko & Magazzu (1996)). From this point of view, RZ Psc is not any more a young star. To estimate its age, we used the rough calibration of Li excess as a function of age for clusters of different ages (King 1993; Soderblom et al. (1990; 1993); Sestito & Randich 2005). Our analysis of these data shows (see Fig. 2) that the excess of Li in the atmosphere of RZ Psc corresponds approximately to a stellar age between the age of the Pleiades (about 70 Myr) and the Orion (about 10 Myr) clusters. It is admittedly a rough estimate, taking into account the high dispersion of Li abundance versus age in both clusters. Nevertheless, this estimate qualitatively agrees with the absence of IR excess in RZ Psc and its isolated position far from the star-forming regions.

3. The kinematic age of RZ Psc

Another possibility to estimate the age of RZ Psc is the proper motion of the star. According to the Tycho-2 catalog by Hog et al. (2000), the proper motion of RZ Psc is quite large: pmRA = 25.4 ± 2 mas yr^{-1}, pmDE = -11.9 ± 2.1 mas yr^{-1}. The corresponding values of the proper motion in the galactic coordinate system are: pm$l$ = 7.89 ± 0.60 deg. per Myr, pm$b$ = -2.76±0.49 deg. per Myr.

Assuming that RZ Psc has not moved away very far from its birthplace near to the Galaxy plane (GP), one can calculate the vertical component of its motion W using the approximation by Perrot & Grenier (2003) for the gravitation potential of the Galactic disk. In this approximation the Galactic disk is locally described by an infinite plane. The corresponding vertical acceleration is given by

$$g(z) = -4\pi \mathrm{G}\rho_d z_d (1 - e^{-z/z_d}) \,, \qquad (1)$$

where G is the gravitational constant, ρ_d = 7.6 x $10^{-2} M_\odot\, pc^{-3}$ is a volume density at $z = 0$ (Crézé et al. (1998)), z_d = 260±60 pc is an exponential scale height (Ojha et al. (1996)).

Substituting $g(z)$ in the right part of equation of motion in z- direction and replacing dW/dt by $W dW/dz$, after integration on z we obtain the vertical component of the velocity

$$W(x) = \pm\sqrt{W_0^2 - v_d^2\, f(x)} \,, \qquad (2)$$

where $x = z/z_d$,

$$f(x) = x - 1 + e^{-x} \,, \qquad (3)$$

$$v_d = 2 z_d (2\pi G \rho_d)^{1/2} \,, \qquad (4)$$

W_0 is the initial velocity at $x = 0$. Signum "+" in Eq. (2) corresponds to the motion toward the southern Galactic pole.

Equation (2) describes the oscillations of a star in the gravitation field of the disk after ejection from the disk plane with the initial velocity W_0: at some point x_m the velocity W drops up to zero, whereupon the star goes back, intersects the disk plane, and continues the motion at the opposite side of the disk plane. With Eq. (2) we can calculate the time of the star motion from x_1 to x_2 ($x_2 \leq x_m$):

$$t(x_1, x_2) = t_d \int_{x_1}^{x_2} \frac{dx}{\sqrt{a^2 - f(x)}} \,, \qquad (5)$$

Here $a = W_0/v_d$, $t_d = z_d/v_d \approx 12$ Myr. The time $t(0, x_m)$ = $p/4$, where p is the period of oscillations of a star in the gravity field of the disk. If the current value $W(x) > 0$ (the star moves away the Galactic plane), then the kinematic age $t_k = t(0, x)$. In the opposite case $t_k = p/4 + t(x, x_m)$.

Accordingly, we need two parameters to calculate t_k: a) the current distance z of the star from the disk plane, and b) the corresponding velocity $W(z)$. Both parameters depend on the distance to the star D: i) $z = D \sin b - z_\odot$, where $z_\odot$ is a distance of the Sun from the Galactic plane (in pursuance Joshi (2007) we adopt $z_\odot$ = 25 pc); ii) $W(z) = V_r \sin b + D$ pm$b \cos b + W_\odot$, where pm$b$ is the proper motion of RZ Psc in ster/sec, $W_\odot$ = -7 km/sec is the velocity of the Sun toward the nordic Galactic pole (Perrot & Grenier 2003), $V_r = -11.5 \pm 1.5$ km/sec - the radial velocity of the star (Kaminski et al. 2000). For the estimate of D, we used the photometric data for the out-of-eclipse state of RZ Psc ($V \approx 11.5^m$, Zaitseva (1985)) and adopted T_{ef} = 5250 K, $\log g$ = 4.0 (see above), and the stellar radius $R_* = 1.5 R_\odot$ (which is compatible with $\log g = 4.0$ at $M_* \approx 1\, M_\odot$). The interstellar extinction toward RZ Psc $A_V \approx 0$ (Kaminski et al. 2000). Taking this into account we obtain $D \approx 240$ pc[2]. Using this value at the calculations of z, z_m and $W(z)$ we obtain t_k = 37.6±5.4 Myr. Here, the uncertainty is due to the uncertainty of pm$b$ (-2.76±0.49 deg/Myr). About the same uncertainty appears at the variations of D within 240±50 pc: $t_k = 37.6^{-7.2}_{+6.9}$ Myr. Taking this into account we can give an approximate estimate of the kinematic age of the star: $t_k \simeq$ 30-40 Myr[3].

Thus, both estimates of the age of RZ Psc, based on the lithium excess and the proper motion of the star give values that essentially exceed the characteristic time of dissipation of protoplanetary disks ($\sim$ 10 Myr; Strom, Edwards & Skrutskie (1993)). This allows us to classify RZ Psc as an intermediate object between MS stars with debris disks and UXOrs.

4. Discussion and conclusion

The question arises: if RZ Psc is a post UXOr, what is, in this case, the reason for the quick and sporadic eclipses of the star? The apparent answer would be a screening of the star from time to time by material remnant from the CS disk: planetesimals, comets, and rocks orbiting the star and dissipating in its nearest vicinity.

The idea of comet-like activity in the neighborhoods of young stars as a possible source of the variable CS extinction is not new. It was claimed many years ago by Gahm & Greenberg (1983). However, in the case of young stars, there is a power alternative source of the variable extinction: the inhomogeneous matter of CS disks. This source dominates in UX Ori stars. Therefore, the case of RZ Psc is interesting and important because there are no alternative explanations for the rapid and sporadic eclipses of the star.

Using the flux variation rate (about 0.1 mag. per hour) estimated by Zaitseva (1985) from intense photometric monitoring of two deep minima of RZ Psc, one can estimate the tangential velocity v_t of the opaque screen (the dust cloud) intersecting the line-of-sight and its approximate distance to the star. Assuming an stellar radius of R_* = 1.5 $R_\odot$ and stellar mass of M_* = 1 $M_\odot$, we obtained $v_t \approx 40\ \mathrm{km\,s^{-1}}$ and a distance ≈ 0.6 AU. In order to screen the star from an observer during two days (the duration of eclipses), the clouds have to be quite compact (about 0.05 AU).

The further study of RZ Psc and the search for stars with similar properties can give valuable information about the disk properties at the transitional phase of their evolution. It is important, first of all, to observe the mid-IR excess of this star at $\lambda \geq 5\ \mu$m. There are indications that this excess exists, including the observations of the highly polarized radiation in the deep minima (Kiselev, Minikulov & Chernova (1991), Shakhovskoi, Grinin & Rostopchina (2003)) and the so-called blueing effect (Zaitseva 1985, Kardopolov, et al. 1980, Pugach 1981). Both these effects are caused in UX Ori stars by the scattered radiation of CS dust (Grinin (1988)). This radiation is the relatively stabilized agent (different in different stars), which provides the limitation of the amplitudes of the algol-type minima. For RZ Psc $(\Delta V)_{max} \approx 2.5$, which corresponds to the intensity of scattered radiation $I_{sc} \approx 0.1 I_*$, (which is comparable with the level of I_{sc} in the other UXORs (Grinin et al.

[2] At this distance, the proper motion of RZ Psc would correspond to a tangential velocity $\simeq 32\ \mathrm{km\,s^{-1}}$

[3] Note that the kinematic age of RZ Psc is comparable with the age of the Gould Belt, a nearby starburst region where many stars have formed over 30 to 40 Myr ago (see Perrot & Grenier (2003), and references there). This allows us to assume that RZ Psc is a runaway member of this cluster.

1991). The absence of near IR excess in RZ Psc means that in this case the main part of CS dust lies far from the star, in the circumbinary disk. This dust is probably formed (as in MS stars with debris disks) by collisions of large particles, rocks, and planetesimals (see. e.g. Wyatt (1996)) and is heated by stellar radiation. The energy distribution of RZ Psc at mid-IR wavelengths will enable us to estimate the characteristic size of the region occupied by CS dust. The other important problem is to find the distance from the star. It allows us to estimate more precisely the time when RZ Psc has left its birthplace.

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References

Bouvier, J. 2008, A&A, **489**, 53
Crézé, M., Chereul, E., Bienymé, O., Pichon, C. 1998, A&A, **329**, 920
da Silva L., Torres, C.A.O, de la Reza R. et al. 2009, A&A, **508**, 833
Dullemond, C. P., van den Ancker, M. E., Acke, B. & van Boekel, R. 2003, ApJ, **594**, L47
Gahm, G.H., & Greenberg, J.M. 1983, in *Asteroids, Comets, Meteors*, eds. by C.-I. Lagerkvist & H. Rickman, Uppsala Univ. 375
Galazutdinov, G.A. 1992, SAO Preprint, N 92
Glass, I.S. & Penston, M.V. 1974, MNRAS, **167**, 237
Grinin, V.P. 1988, Soviet. Astron. Lett. **14**, 27
Grinin, V.P., Kiselev, N.V., Minikulov, N.H, Chernova, G.P. & Voshchinnikov N.V. 1991, ApSS, **186**, 283
Grinin, V., Stempels, H.C., Gahm, G.F., et al. 2008, A&A, **489**, 1233
Herbig, G.H. 1960, ApJ, **131**, 632
Hog, E., Fabricius, C., Makarov, V. V. et al. 2000, A&A, **355**, L27
Joshi, Y.C. 2007, MNRAS, **378**, 768
Kaminskii, B.M., Kovalchuk, G.U. & Pugach, A.F. 2000, Astronomy Reports, **44**, 611
Kardopolov, V.I., Sahanionok, V.V. & Shutemova, N.A. 1980, Perem. Zvezdy, **21**, 310
King, J., 1993, AJ, **105**, 1087,
Kiselev, N.N., Minikulov, N.K. & Chernova, G.P. 1991, Astrophysics, **34**, 175
Kupka, F., Piskunov, N.E., Ryabchikova, T.A., Stempels, H.C., & Weiss, W.W. 1999, A&A, **138**, 119
Kurucz, R. 1979, ApJS, **40**, 1
Natta, A., Prusti, T., Neri, R., et al. 2001, A&A, **371**, 186
Ojha, D.K., Bienymé, O., Robin, A.C. et al. 1996, A&A, **311**, 456
Pavlenko, Ya.V. & Magazzu, A. 1996, A&A, **311**, 961
Perrot, C.A. & Grenier, I.A. 2003, A&A, **404**, 519
Piskunov, N.N. 1992, in *Stellar Magnetizm*, eds. Yu.V. Glagolevsky & I.I.Romanjuk, (St. Petersburg, Nauka), 92
Piskunov, N.E., Kupka, F., Ryabchikova, T.A., Weiss, W.W. & Jeffery, C.S. 1995, A&A, **112**, 525
Pugach, A.F. 1981, Astrophysics, **17**, 47
Sestito, P. & Randich, S. 2005, A&A, **442**, 615
Shakhovskoi, D.N., Grinin, V.P. & Rostopchina, A.N. 2003, Astronomy Reports, **47**, 580
Soderblom, D.R., Jones, B.F., Balachandran, S., et al. 1993, AJ, **106**, 1059
Soderblom, D.R., Oey, M.S., Johnson, D.R.H., Stone, R.P.S. 1990, Astron. J., **99**, 595
Strom, S.E., Edwards, W. & Skrutskie, M.F. 1993, in *Protostars and Planets* III, (ed. E.H. Levy & J.I. Lunine), 837, (University of Arizona Press, Tucson)
Wyatt, M. 2008, Ann. Rev. Astron. Astrophys. **46**, 339
Wenzel, W. 1989, Inform. Bull. Var. Stars. **3280**, 1
Zaitseva, G.V. 1985, Variable Stars, **22**, 181