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Probing the structure and dynamics of the RZ Psc dust disk via long-term optical and mid-infrared variability

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Abstract

Combining new and earlier available photometric observations of the isolated post T Tauri star RZ Psc in the optical and the MIR we try to constrain possible mechanisms of variability at different time-scales. The MIR variability features a very consistent color temperature, 800K, of the variable component across timescales from days to years. New observations confirm the existence of long-term cyclicity in optical variability. Our new estimate of its period is 14.2 years. We did not find similar long-term cyclicity in MIR variability. The most prominent increase of MIR flux coincides with the accretion episode observed spectroscopically in 2014 [1]. Analysis of color index variability in the visible suggests the dominance of submicron sized ISM-like dust on the line of sight for both short-term stochastic and long-term cyclic variability. Based on these findings we suggest that the most probable source of observed features is dust driven by disk wind from primordial disk, not the dust produced by collisions in an extremely disturbed debris disk [2],[3].

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1 Introduction

RZ Psc is a unique star of solar mass at high galactic latitude manifesting many characteristic features of young stellar objects. The most prominent feature is UXOR[4] type photometric variability with deep aperiodic minima, the blueing effect and high degree of polarization observed in those minima [5],[6],[7]. Apart from the minima

there is multiyear low-amplitude modulation of the bright state, also a typical feature among UXORs [8].

The age of RZ Psc is estimated to be in the range of 20-40 M years by kinematic considerations and lithium abundance [9],[10]. That corresponds to the Post T Tauri evolutionary stage, which is associated with final stages of planetary system formation and final dissipation of protoplanetary disk. Signatures of a rather massive dust disk around RZ Psc: about 0.05 of stellar luminosity scattered [7] and about 0.08 thermally reradiated [2] by dust, suggest it is a rare case of considerably large disk retained or regenerated at this age.

The study of such an extreme case might be beneficial for general understanding of this evolutionary stage. De Wit et al [2], who discovered the thermal dust emission in RZ Psc and Su et al [3], who studied its variability and marginally resolved its spatial structure, interpret unusual amount of dust present close to the star by the collisional mechanism typical for debris disks of such age, but with collision frequency extremely heightened by some disturbing influence. On the other hand, there are reasons to think that a large amount of primordial disk material is still present in this system. The dust on the line of sight obscuring the star during deep minima is similar to the ISM dust by grain size, as evidenced by observed reddening [7]. And there is evidence for the gas component of primordial disk: clumpy outflows observed as short-living blue-shifted absorptions in Na D lines and accretion-attributed emission cores of Balmer lines [1], [10]. We studied both the thermal signatures of dust on the time interval comparable with the putative photometric period of about 12 years [2] and the optical signatures of dust on the line of sight in order to find extra evidence able to clarify the nature of RZ Psc disk.

2 Observations and data reduction

Most of our mid-infrared data overlap with the dataset used by Su et al [3], consisting of Spitzer [11] photometry in the 3.6μ and 4.5μ bands and WISE photometry in the 3.4μ and 4.6μ (W1, W2) bands. We added a few later epochs of WISE observations absent in the those data. WISE observations are mostly data of the NEOWISE [12] part of the mission, when the telescope and detectors operated uncooled. Therefore the S/N ratio for single images is rather poor. In order to extract maximum value from these data we tried two reduction procedures: 1) single aperture photometry data provided by NEOWISE and 2) differential aperture photometry with raw images using TYC 1753-1888-1 as a comparison star. We found that single photometry produced less scattered series, but with a few big outliers for images of imperfect quality. The differential photometry series had no such outliers. In further analysis we used more robust differential photometry data averaged over groups spanning a few days each, yielding a series with the time resolution of about 150 days and the typical rms error less than 0.05^m .

Optical observations consist of three parts: 1) the whole V band dataset used to analyze optical variability in [2], spanning 1972 to 2012; 2) ASASSN data covering years 2013 to 2024 in the v and g bands. The g band observations were converted to v by adding constant corrections determined using available same night observations;

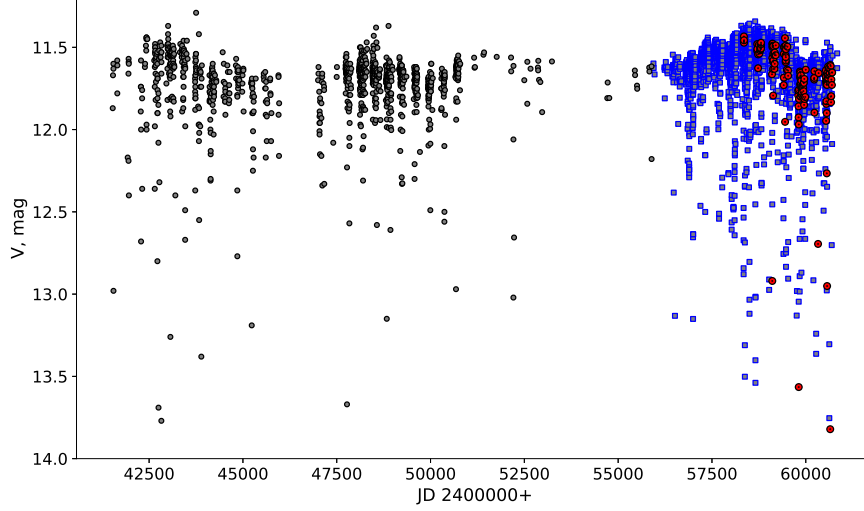


Fig. 1 Combined V band lightcurve of RZ Psc. Data sources: [2] - black dots; ASASASN - blue squares; Our observations - red dots.

3) new observations in 2018-2025 at CrAO 1.25m AZT-11 telescope using FLI PL230 CCD with VRI filters close to the Johnson-Cousins system, 137 nights in total. These data are available via request to authors. TYC 1753-1888-1 was used as a comparison star, BD +27 182 and TYC 1753-1926-1 as check stars. These observations were reduced using standard procedures for aperture photometry in Maxim-DL software. For color variability only this set of homogenous observations was used, therefore no conversion to standard Johnson-Cousins systems was done, data used in the analysis are in the instrumental system. The compound historical lightcurve is presented in Fig 1.

3 Analysis and discussion

3.1 Long-term cyclicity

Multi-year low amplitude variability of RZ Psc, evident in long-term photometric series, is a characteristic feature of many UX Ori type stars [8]. The estimates of its period [8], [2] are rather imprecise due to the difficulty of decoupling this component of variability from the deep minima and uneven temporal coverage of observations. There is no natural cut-off magnitude to use for the deep minima filtering. De Wit et al [2] picked cut-off value yielding maximum power in the low-frequency range of the Lomb-Scargle periodogram of the cleared series. Looking for a less arbitrary method we tried two alternative techniques: 1) Select the cut-off level producing minimal skewness of the cleared series distribution, assuming all the skewness of raw series is due to deep minima. 2) Use no cutoff, select the brightest state observed each year. This yields a nearly equidistant series with one year time resolution. To mitigate the varying number of observations between years, the number of observations in a given

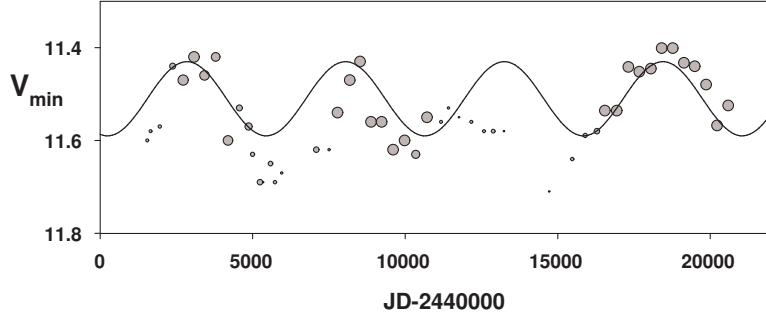


Fig. 2 The weighted yearly minimal magnitude dataset (see text). Each circle is a minimal observed V magnitude, size of circles is proportional to the number of used observations

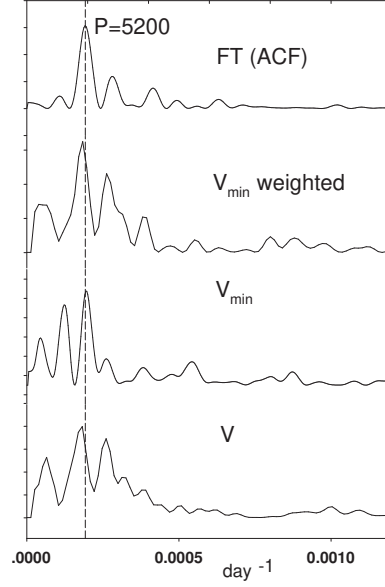


Fig. 3 Periodograms of cleared V lightcurves (see text). Bottom to top: Lomb-Scargle (LS) of the minimum-free series; LS of the yearly minimal magnitude, unweighted; LS of the yearly minimum magnitude, weighted; Power spectrum of the autocorrelation function.

year is used as a weight of corresponding datapoint. The resulting series of those yearly minimal magnitudes is presented in Fig 2.

To estimate the period or characteristic time of long-term variability we used Lomb-Scargle periodograms of the minima-free series described above and an ACF-based periodogram of raw series. All periodograms feature a broad peak around 5000 days (Fig 3) while the position of its maximum varies from one method to another. We

accept the value of 5200 days or 14.2 years as the best combined estimate. This is evidently not a strictly periodic process, the better description is a QPO with a spectral window 6 to 20 years.

3.2 Mid-Infrared variability

As Fig 4 demonstrates, the 14 years cycle is not present in the MIR variability. This in itself provides some constraints on its possible interpretations. If long-term optical variability was caused by the variations of intrinsic stellar luminosity, MIR excess resulting from thermal reprocessing by dust would vary in exactly the same way. If the 14 years cycle is due to variable obscuration by dust, it is not the hot dust producing the MIR excess, but a part of a separate structure, presumably formed by colder dust.

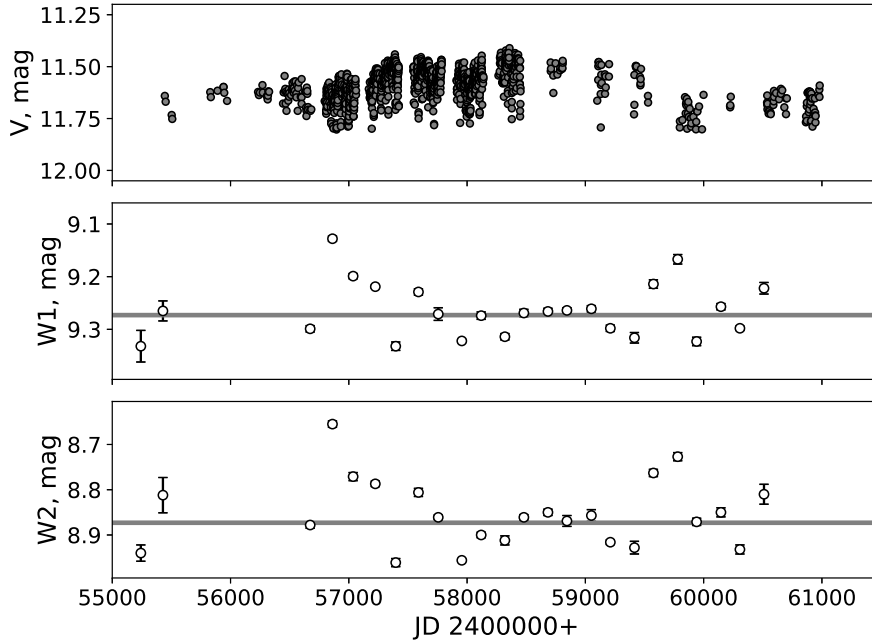


Fig. 4 Upper plot - V band lightcurve, cleared of the deep minima, g-band ASASSN data excluded; middle and bottom plots - WISE W1 and W2 bands (binned values, error bars designate intra-bin rms errors). Bold horizontal lines are average values for W1, W2.

Apart from stochastic variations of MIR flux, the interesting feature of the lightcurve is a year-long spike observed around JD 2457000 (year 2014). This coincides with the period when enhanced line emissions were observed, interpreted as an episode of accretional activity accompanied by the increase in disk wind [10]

This spike is regarded by Su et al [3] as an extreme collisional event(s). But the coincidence with an accretion episode suggests that the extra dust might be brought by some kind of disk or X wind. Wind dragging dust from the disk midplane, and so exposing it to stellar radiation is also often suggested to explain variability of TTS

[13]. There is a less prominent spike around JD 24599700. Without concurrent spectral observations it is not clear if its nature is the same as the 2014 spike.

In order to estimate the temperature of the dust responsible for MIR variability we considered W1 vs W2 and 3.6μ vs 4.5μ flux correlation (Fig 5). High linearity of the dependence suggests the same and constant effective temperature for all observed MIR variability: days to weeks stochastic variability sampled by Spitzer data, ≈ 100 days variations sampled by WISE, and the spike of 2014.

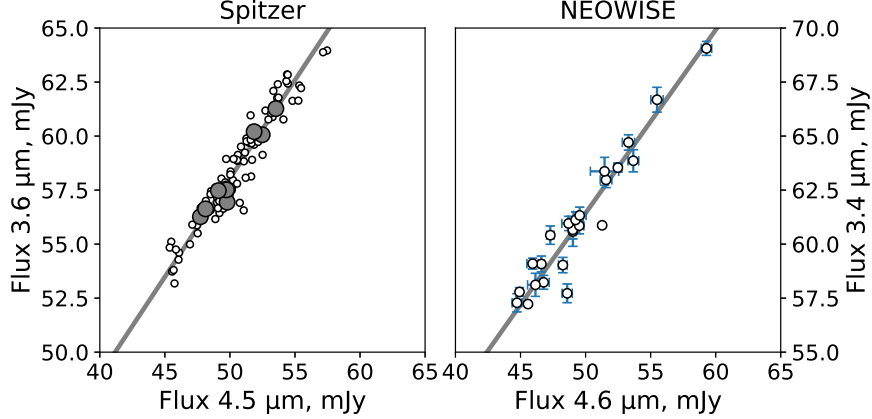


Fig. 5 Flux vs flux plots for WISE and Spitzer observations with lines of regression used to estimate the effective temperature of the variable component.

The black body temperature of the variable component estimated by the slope of regression is $830 \pm 40K$ for WISE data and $790 \pm 20K$ for Spitzer data. Constant effective temperature suggests that geometry of the radiating dust structure is always the same, what changes is the amount of dust feeling it. It is notable that temperature is significantly higher for this variable component than the SED-derived disk-averaged estimate of $500K$ [2]. This also better fits the wind mechanism of dust supply. The dust dragged by the wind eventually forms a stable structure at a larger distance. When the dust is collisionally generated in a gas-poor environment of a debris disk, it is predominantly $\geq 1\mu$ gains drifting inward due to the Poynting-Robertson effect, not outward. The region of the dusty wind presumably generating MIR variability, based on the $800K$ temperature, must be at about $0.15a.u.$ or $30R_*$ from the star.

3.3 Color variability and the dust on the line of sight

While reddening during the deep minima of RZ Psc is well studied by now, the character of color variations intrinsic to the long-term variability has been unknown so far. The low amplitude of the long term variability and slight differences in photometric systems make long combined datasets unfit for this purpose. We used our homogeneous series of VRI photometry at AZT-11 to analyze color variability at long timescale and low amplitude. Deep minima were excluded from consideration with cutoff value

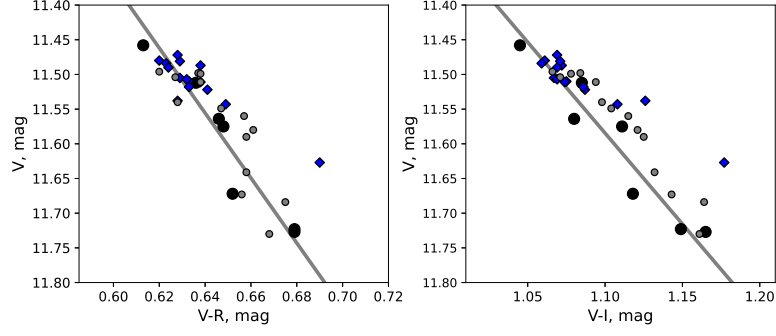


Fig. 6 V vs color index diagrams for selected seasons of VRI photometry at AZT-11 (deep minima excluded). Small circles for the year 2021, diamonds for 2019, big circles for yearly averaged values. The regression lines are for average values

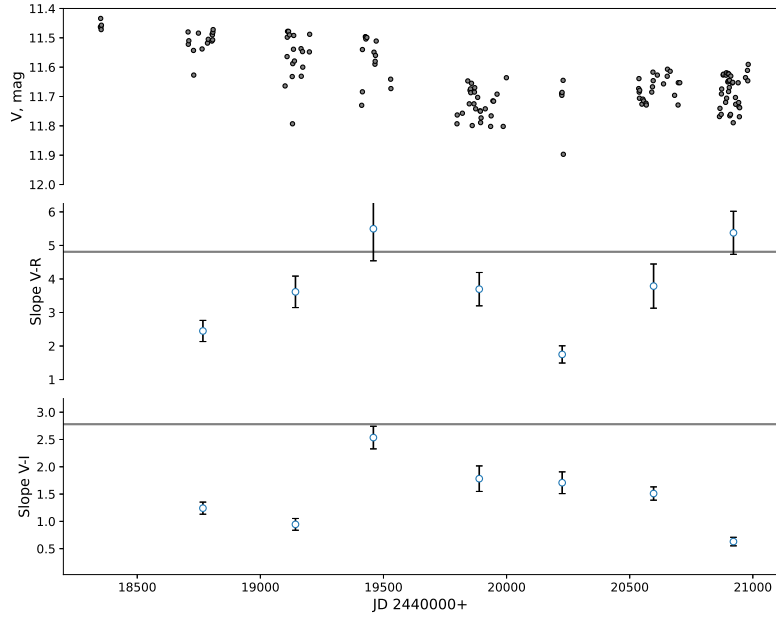


Fig. 7 The V lightcurve for the VRI photometry at AZT-11 with deep minima excluded (upper plot) and estimations of reddening coefficients. Bold horizontal lines mark the values of reddening coefficients for yearly averaged data

$V = 11.85^m$. We estimated V vs V-R, V vs V-I reddening slopes individually for each observing season in years 2019 to 2024, and for yearly averages (Fig 6, Fig 7). The difference of reddening slope between years is only marginally significant. The slope for averaged values characterizing long term variability is significantly steeper than for individual seasons. The range of derived reddening coefficients, 2 to 5 for $A_V/E(V-R)$ is within the typical for ISM and YSO dust.

4 Conclusion

Based on the evidence provided by the optical and MIR variability, the main features of RZ Psc system are as follows: There is a variable stream of dust lifted from a geometrically thin disk, presumably a remnant of a primordial protoplanetary disk. This dust is likely dragged by the X or other type of disk wind originating from the nearest vicinity of the star ($\approx 30R_*$). The dust on the line of sight responsible for the 14 years cycle of low amplitude optical variability belongs to a different structure which is also distinct from the compact dust clumps causing short minima and stochastic variability, distinguished by different reddening law, corresponding to larger effective grain size in the dust responsible for long-term variability.

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