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Unusual Eclipse of the UX Ori Type Star V719 Per

V. P. Grinin[a, b, *], O. Yu. Barsunova[a], S. G. Sergeev[c], S. Yu. Shugarov[d, e], and E. I. Fedorova[b]

[a] *Central (Pulkovo) Astronomical Observatory, Russian Academy of Sciences, St. Petersburg, Russia*
[b] *St. Petersburg State University, St. Petersburg, Russia*
[c] *Crimean Astrophysical Observatory, Russian Academy of Sciences, Nauchnyi, Russia*
[d] *Sternberg Astronomical Institute, Moscow State University, Moscow, Russia*
[e] *Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica, Slovakia*
**e-mail: vgcrao@mail.ru*

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Abstract—The results of new photometric (VRI) observations of the young star V719 Per from the IC 348 cluster are presented. Up until 2014, this star demonstrated brightness variability typical for UX Ori stars, i.e., caused by strong fluctuations in circumstellar extinction. In 2014, the star dimmed by approximately 3 magnitudes in the I band and remained in that state until 2017. There is reason to believe that the eclipse was caused by a disturbance in the innermost regions of the star's protoplanetary disk. The dust raised above the disk caused the star's radiation to be blocked for approximately three years. The role of various processes in the generation of such disturbances is discussed.

Keywords: young stars, variable circumstellar extinction, protoplanetary disks, stellar magnetosphere, V719 Per

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1. INTRODUCTION

The star V719 Per (spectral type M1.25 [1]) belongs to the young cluster IC 348 and is one of the coldest variable UX Ori stars known to date. The first indications of this type of variability caused by the star being eclipsed by fragments of its own protoplanetary disk were obtained for V719 Per in [2–4]. The observations made by those authors showed that the star dims from time to time by a few tenths of a stellar magnitude. The more extended photometric monitoring performed by our group [5] showed that this star has much deeper brightness minima with an amplitude up to 3^m in the I band. During such events, the color indices on the color–magnitude diagram shift toward blue, demonstrating the so-called "extinction effect" characteristic of UX Ori stars and caused by an increase in the contribution of scattered light from the protoplanetary disk to the observed radiation [6]. In the case of V719 Per, this effect was first observed in [5]. The authors of [7, 8] suspected periodicity in the brightness variations of the star, which, however, was not confirmed by longer observations [5].

An important feature of V719 Per is that it is one of the few young stars that belongs to the UX Ori family. At the same time, it is a weak line T Tauri star (WTTS). These stars are characterized by a low accretion rate. For this reason, despite the low effective temperature of V719 Per (T_{eff} = 3669 K [1]), no signs of activity caused by hot accretion spots were found in its photometric behavior. According to the data [9] based on the modeling of the energy distribution in the spectrum of the star, the central part of its circumstellar disk has a cavity with a radius of about 0.7 AU, loosely filled with matter. Thus, the consequence is the absence of a noticeable infrared excess of radiation in the near infrared (IR) part of the spectrum. The formation of such a cavity is often associated with the formation of a planetary system in the inner region of the protoplanetary disk. Its existence is the cause for the low accretion activity of the star and, as a consequence, the weak emission activity ($EW(H_\alpha) < 2$ Å [10]).

On the other hand, the photometric activity of UX Ori stars, caused by strong fluctuations of circumstellar extinction at the line of sight, suggests a slight tilt of the protoplanetary disks of stars relative to the direction toward the observer [11]. In the case of V719 Per, this is also indicated by the large absorption in the direction toward the star ($A_V \simeq 2.8^m$ [1]). With this orientation, photometric monitoring of the star provides a unique opportunity to study nonstationary processes in the disk, which can raise dust above its surface and affect circumstellar extinction. Furthermore, we consider the properties of the photometric activity of V719 Per considering new observations carried out during six observational seasons from 2014 to 2020.

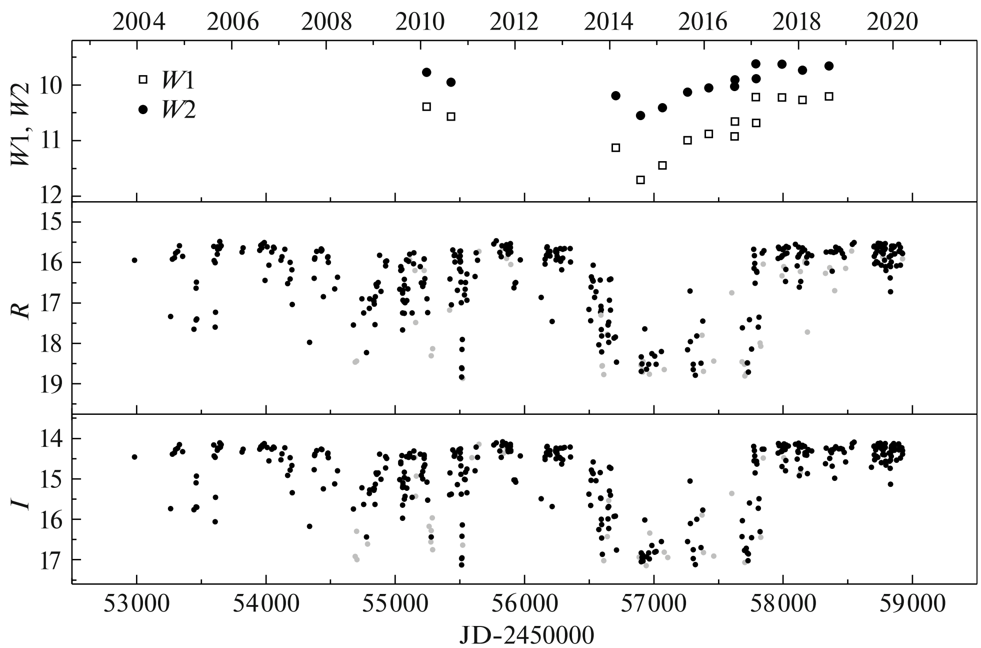

Fig. 1. Light curves of V719 Per in the R and I bands. The gray dots show the observations with an error $0.15^m \le \sigma \le 0.4^m$. At the top are the IR data in the $W1$ and $W2$ bands from the WISE archive.

2. OBSERVATIONS

Same as in the previous studies of our group, the optical observations of V719 Per were performed at the AZT-8 (0.7 m) telescopes of the Crimean Astrophysical Observatory of the Russian Academy of Sciences and G2 (0.6 m) telescopes of the Slovak Academy of Sciences equipped with CCD photometers. The observations were performed in three photometric bands v, r, i and were reduced to the Johnson–Cousins photometric system V, R_C, I_C. Since all the photometric parameters are further given in this photometric system, we omit the subscript "C" for simplicity. The details of the observations and aperture photometry of the CCD images are given in [5]. The photometry accuracy at the brightness maximum of V719 Per is, on average, 0.03^m in all three bands V, R, I. At deep minima, the accuracy drops to 0.3^m in the R and I bands. In the V band at deep minima, the brightness of the star decreased to 20.5^m and the photometry accuracy in that state was about approximately 0.5^m. In addition to optical photometry, in our paper we also use IR observations in the $W1$ (3.4 μm) and $W2$ (4.6 μm) bands from the WISE archive [12].

3. RESULTS

Figure 1 shows the light curves of V719 Per in the R and I bands supplemented with observations in two IR bands $W1$ and $W2$ from the WISE archive [12]. As observed in the bright state, the brightness of the star fluctuates near the values $I \simeq 15.5^m$, $R \simeq 14.3^m$. From time to time, the star experiences dimming with an amplitude of up to 3^m and duration on the order of few days. At the beginning of 2014, the star's brightness did not return to its original state after another drop, and the star remained in a dimmed state for approximately three years. In 2017, it brightened again and returned to its original bright state. It can be seen from Fig. 1 that during the optical minimum the star also dimmed in the IR bands $W1$ and $W2$. Although those observations were few, it can be seen that the shape of the IR minimum of 2014–2017 does not completely match the shape of the optical minimum.

Thus, the most interesting event in the photometric life of V719 Per is the deep ($\Delta m \approx 3^m$) and prolonged minimum in brightness observed for three years from 2014 to 2017. The rapid entry into the minimum and even faster exit, combined with a long duration, make this event unlike all previously observed minima of UX Ori stars. It is interesting that in three observational seasons following this eclipse, we did not witness a single deep minimum in the brightness of V719 Per. Such a relatively quiet state of brightness was not seen during all our previous observations of this star.

Figure 2 shows the color–magnitude diagram $I/(R-I)$. It was constructed using observations with an accuracy no worse than 0.15^m. The circles show the

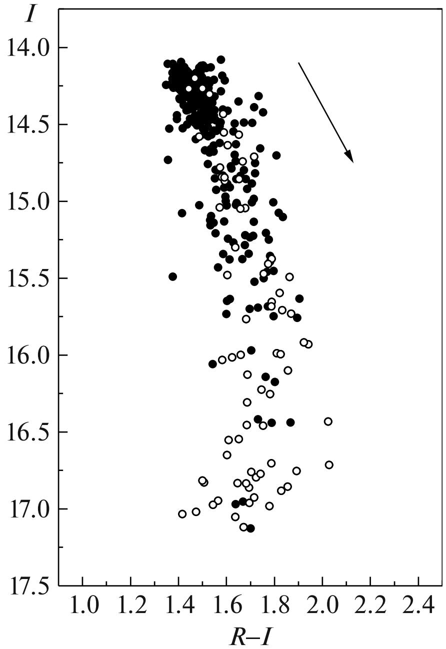

Fig. 2. $I/(R–I)$ color–magnitude diagram. The circles mark the data related to the extended eclipse of 2014–1017. The arrow shows the direction of the standard interstellar reddening law for $A_V = 1^m$.

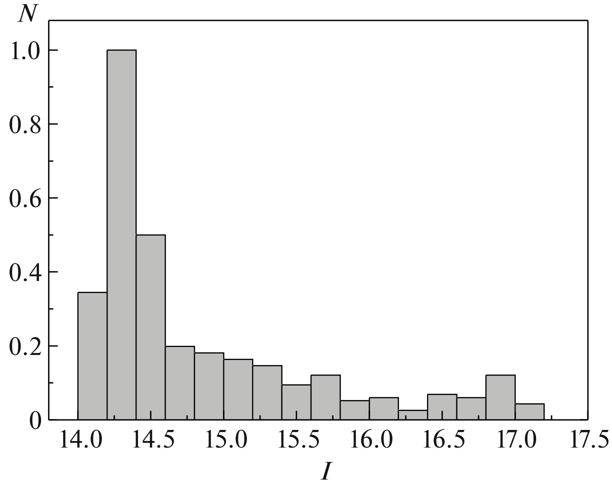

Fig. 3. Normalized histogram of the V719 Per photometric activity in the I band.

data related to the 2014–1017 eclipse. It can be seen that the variations in the color index $R–I$ of the star during that eclipse were approximately the same as during the shorter eclipses observed in previous years: the star first reddens, then the color index $R–I$ begins to decrease with a continuing decrease in brightness. This means that the optical properties of dust during all those eclipses were approximately the same. The color index $V–I$ on the diagram $I/(V–I)$, which we do not show here, varies in a similar way.

4. DISCUSSION AND CONCLUSIONS

From the optical light curves of V715 Per (Fig. 1), as well as from the histogram of the star's photometric activity (Fig. 3), it can be seen that in each photometric band there is a threshold value of the minimum brightness, in which the star does not dim. This limitation on the amplitude of eclipses is an important observational feature of all UX Ori stars. In early studies of these stars, this feature was considered incompatible with the variable circumstellar extinction model (see, e.g., the review [13]). In fact, its origin does not contradict this model and is explained by the existence of scattered radiation from protoplanetary disks [6]. In photometric observations, this radiation is detected together with the direct radiation of the star and in a bright state usually makes a very small contribution to the observed radiation. However, when the star is completely hidden from the observer by the dust fragment of the disk, the scattered light dominates the observed radiation, which prevents a further decrease in the object's brightness. This feature of UX Ori stars also explains, as noted in the Introduction, other effects observed in them, such as the blue shift in the color indices during deep minima, as well as an increase in linear polarization with decreasing brightness [11].

Thus, the amplitude of the brightness attenuation $(\Delta m)_{\max}$, maximally possible due to the above limitation, is related to the intensity of the scattered radiation from the disk I_{sc} by a simple expression: $(\Delta m)_{\max} = 2.5\log(1 + I_*/I_{sc})$, where I_* is the radiation intensity of a star without a disk. Knowing the $(\Delta m)_{\max}$ value from observations, we can very simply estimate the contribution of the scattered radiation to the radiation of the star. As noted above, in the I band the value $(\Delta m)_{\max} \simeq 3^m$. Hence it follows that the contribution of the scattered radiation from the disk to the radiation of V719 Per in the bright state in this band is approximately 6%, which roughly corresponds to the average value of this relation (approximately 10%) for UX Ori stars [11].[1]

It should be noted that prolonged eclipses are observed from time to time in other UX Ori stars as well (see, e.g., [15–19]). Interestingly, a decrease in

[1] It should be emphasized that the scattered radiation of the protoplanetary disk is not constant. On the contrary, I_{sc} continuously fluctuates due to variations in the illumination conditions of the disk by the star, caused by fluctuations of circumstellar extinction in the inner regions of the disk. This explains the scatter of points in the brightness dependences of the polarization parameters of UX Ori stars [11]. In young stars observed from polar directions, such fluctuations cause the appearance of shadows in the images of the disks observed with interferometers in the near-IR part of the spectrum [14].

brightness in the visual part of the spectrum during such events was often accompanied by an increase in the radiation flux in the near-IR range [20–27]. This indicates that such eclipses were caused by the appearance of a large amount of hot dust above the circumstellar disk in the immediate vicinity of the young star. In [23] and [24], a dusty disk wind was considered as a possible source of such dust. However, other mechanisms for raising dust above the disk are also possible. For example, as shown in [28], circumstellar dust ionized by X-rays can rise to a great height in the magnetic field of the disk, increasing its effective geometric thickness. The dust can also be lifted up above the disk by a cyclonic vortex (see, e.g., [29]). In this case, the eclipses of the star will repeat until the vortex fades. Such repetitive and weakening in amplitude eclipses were observed in [30] for a UX Ori star WW Vul. The appearance of dust above the protoplanetary disk can be caused by catastrophic collisions between large planetesimals with the subsequent formation of clouds of fine dust. Such collisions are evidenced by bursts of IR radiation in the spectrum of the debris disk of the star ID8 (2MASS J08090250-4858172), which is a young (35 Myr) solar analogue [31]. Finally, dust between the star and the observer can appear as a result of gas and dust fragments from the remnants of the protostellar cloud falling onto the disk. This model of nonstationary accretion was proposed in [32] and is considered by some authors as a possible source of FU Ori outbursts (see [33] and references therein).

In all of the above models, it is difficult to expect a rapid change in the circumstellar extinction required to explain the fast onset and equally fast completion of the 2014–2017 minimum. Apparently, we can also exclude the possibility that this minimum was caused by the transit of a dusty fragment of the circumstellar disk across the star's disk, since it is not clear how an extended structure limited in azimuth by sharp boundaries can arise under the conditions of differential rotation of the quasi-Keplerian disk. Given the low luminosity of the star ($L \simeq 0.28\ L_\odot$, [1]), it can be assumed that the role of such a screen is played by circumstellar dust, which penetrates directly into the star's magnetosphere. This possibility was recently considered in [34] in relation to the T Tauri star V715 Per, which demonstrates complex brightness variability due to variations in the circumstellar extinction. It was shown that the dust can move with the gas in the magnetosphere for some time before sublimating and screen the radiation of the star. The luminosity of V719 Per is approximately 5 times less than that of V715 Per. Therefore, if dust can be present in the V715 Per magnetosphere, it can penetrate into the V719 Per magnetosphere.

If this is the case, the decrease in the star's brightness in the optical part of the spectrum should be accompanied by an increase in its radiation in the near-IR range. As noted above, this behavior of optical and IR radiation was indeed observed in a number of UX Ori stars during deep minima. In our case, however, according to the WISE data, the IR radiation of V719 Per, on the contrary, *weakened* during the optical minimum (Fig. 1). Thus, the dust screen that blocked the star's radiation covered only a small part of the total solid angle: $\Delta\Omega/4\pi \ll 1$.[2] Since the duration of the eclipse of V719 Per is such that the dust screen should have completely surrounded the star in azimuth, the above limitation on $\Delta\Omega$ holds only if the screen had a small height. This condition can be met if dust penetrates shallowly into the star's magnetosphere. Apparently, this dust barrier could completely screen the star from the observer, provided that the circumstellar disk of V719 Per is tilted at a small angle relative to the direction toward the observer. However, this orientation of the disk is exactly one of the main conditions necessary for the model of variable circumstellar extinction in UX Ori stars.

It should be noted that the penetration of dust even not very deep into the stellar magnetosphere should be accompanied by an increase in the thermal emission of dust in the near-IR part of the spectrum. This additional emission may be one of the reasons for the abovementioned discrepancy between the shape of the eclipse of the star in optics and in the *W*1 and *W*2 bands. Another possible reason may be the insufficiently large optical thickness of some parts of the extended dust screen in the IR spectral range.

Thus, we can assume that the observed minimum brightness of V719 Per could be caused by an increase in the rate of gas accretion onto the star, which lasted for approximately three years. Considering seasonal gaps in the photometric observations, it is possible that such a prolonged eclipse was in fact a sequence of shorter successive decreases in the brightness of the star. In any case, the question arises as to the cause for such a clear localization of this process in time. Considering the unusual form of the eclipse of V719 Per, which has no analogues among the previously observed eclipses of UX Ori stars, further observations of the photometric activity of this star, preferably in combination with spectral and IR observations, are of interest. It would also be important to measure the star's magnetic field.

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[2] Otherwise, the IR radiation of dust in the magnetosphere would be comparable in strength to the radiation of the star itself.

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