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Dust around young stars

Photopolarimetric activity of the classical Herbig Ae/Be star RR Tauri*

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Abstract. The classical Herbig Ae/Be (HAeBe) star RR Tau is known as a highly variable young star with an amplitude of variability of about 4^m in the V pass-band. In this paper we present the results of coordinated Crimea-Dodaira multi-band photo-polarimetric observations of this star which cover fully the observed interval of its brightness changes. Within the observed interval of its light variations the linear polarization of RR Tau anti-correlates with its brightness changes. The dependence of the linear polarization on the stellar magnitude agrees well with the model according to which the main source of the intrinsic polarization of RR Tau is scattered radiation by the circumstellar (CS) disk-like dust envelope (probably the protoplanetary disk) seen edge-on or under a small inclination to the line-of-sight, and that the brightness variations are caused by variable obscuration of the star by revolving circumstellar dust clouds.

A comparison with previous photo-polarimetric observations of this star shows that the Stokes parameters of its polarized radiation are quite stable on a time scale of about 7 years. By using this fact we have separated the interstellar and intrinsic components of the observed polarization. The numerical modeling of the intrinsic linear polarization together with the colour-magnitude diagrams of RR Tau show that the circumstellar disk-like envelope around this star is strongly flattened and that the characteristic size of the grains is intermediate between that of interstellar dust and dust in the old protoplanetary disk of β Pictoris. We assume on the basis of this analysis that RR Tau is surrounded by a young protoplanetary disk and that it can be considered as a young progenitor of β Pictoris.

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* Tables 1 and 2 are only available in electronic form at CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Key words: stars: pre-main sequence – stars: variables – stars: individual: RR Tau – polarization – stars: circumstellar matter

1. Introduction

In this paper we report the continuation of our photo-polarimetric investigations of young stars with non-periodic Algol-type minima, of which UX Ori is a prototype (Bibo and Thé 1991). An important special feature of their polarimetric activity is the clear anti-correlation between brightness and polarization variations (Grinin et al. 1991). This behaviour of the linear polarization is predicted in the framework of the variable CS extinction model and is a result of the screening of the young star by opaque dust fragments (clouds) in its protoplanetary disk (Grinin 1986). When such a star is observed we measure the sum of the direct and the scattered stellar radiation. The former is variable due to the presence of the small clouds which, at times, intercept the stellar light. The latter is constant if it is mostly due to circumstellar dust distributed in a much larger volume, of which the clouds occupy only a small fraction.

The observations at deep minima are especially important. In such episodes the CS dust clouds, intersecting the line of sight, act as a natural coronograph. It allows the observations of the weak scattered radiation of the young protoplanetary disk, somewhat contaminated by direct stellar radiation. High linear polarization (5-8%) which is systematically observed at deep minima indicates that the protoplanetary disks of the UX Ori type stars (below we will use the abbreviation "UXORs" suggested by Herbst et al. 1994) are observed edge-on or somewhat inclined to the line-of-sight. This is probably the main reason of their large amplitude Algol-type variability (Grinin 1992). The investigations of such objects are of great interest for the study of the physics of young stars.

Because of the unpredictable character of the Algol-type minima long-term photo-polarimetric monitoring of the UXORs is needed to cover the whole interval of the brightness changes. Below we present the results of the coordinated photo-polarimetric multi-band observations of the HAeBe star RR Tau made at the Crimean Astrophysical Observatory (CAO) in co-operation with the National Optical Observatory of Japan (Dodaira). Unlike previous objects of our program (UX Ori, BF Ori, WW Vul, CQ Tau etc.) which all are isolated HAeBe stars [1], RR Tau is a classical HAeBe star associated with a weak nebulosity (Herbig 1960).

According to Herbig (1960) the spectral type of RR Tau is B8-9. Strom et al. (1972) estimated it as A3-A5. The difference is caused by the use of different spectral lines for the spectral classification.

The variability range of RR Tau is about 4^m from V = $10\overset{m}{.}2$ to V = $14\overset{m}{.}3$ (Herbig & Bell 1989). The photometric behaviour of this star has been investigated by Rössiger & Wenzel (1974) who observed a complex behaviour of RR Tau in the colour-magnitude diagram $(B-V)$ vs. V (the so-called "turnaround" of the colour-indices). Later a similar "turnaround" in the colour-magnitude diagrams $(U-B)$ vs. V and $(B-V)$ vs. V at deep minima was also observed by Zajtseva (1986). She noted that the star at deep minima can be even bluer in $U-B$ than at the maximum brightness state.

The published polarimetric observations of RR Tau are fragmentary and were not accompanied by synchronous photometry (Breger, 1974; Garrison & Anderson, 1978; Vrba et al. 1979; Hillenbrand et al. 1992). An exception are the works by Kardopolov & Rspaev (1989) and Kardopolov et al. (1994). They observed a decrease of brightness of RR Tau from V = $10\overset{m}{.}8$ to V = $13\overset{m}{.}2$ accompanied by an increase of the linear polarization from P = 1.56$\pm$0.19% up to P = 4.90$\pm$0.93% and by changes of the position angle within about 20°.

In Sect. 2 we present the results of the multi-year photo-polarimetric monitoring of RR Tau which cover the whole interval of its brightness changes [2]. The analysis of the observational data and their numerical modeling are given in Sects. 3 and 4. The main results are summarized in Sect. 5.

2. The observations

Simultaneous five-channel observations of the brightness and polarization of RR Tau were carried out at CAO with the 1.25 m telescope using the Piirola (1975) $UBVRI$ photometer-polarimeter. The observations were started in 1987-1988 by N.K.Minikhulov and were continued in 1992-1995 in cooperation with the Dodaira Observatory. Depending on the observational conditions the 10″or 15″diaphragms were used. At each observing night from 8 to 20 measurements of Stokes parameters were done. We used the star HDE 245817 = BD+26°885 of Shakhovskaya et al. (1986) as the comparison star. The photometric data were reduced to Johnson's $UBVRI$ photometric system. The accuracy of the photometric data is $0\overset{m}{.}02$ in $U-B$ and in V and is $0\overset{m}{.}01$ in the other colour indices. At deep minima or at nights with the poor seeing conditions the accuracy is lower by about three times. The correction of the polarimetric measurements for instrumental polarization was made by the observations of polarimetric standards.

Table 1[3] presents the photometric and polarimetric observational data for RR Tau obtained at CAO. The total number of the observational nights is 117.

The observations at Dodaira were obtained from 1992 to 1994 at seven pass-bands (0.36, 0.41, 0.46, 0.53, 0.65, 0.70 and 0.76 μm) with a multi-channel polarimeter (Kikuchi 1988) mounted on the 0.91-m telescope. The observations were done with 15″diaphragms. The photometric and polarimetric observations were always done simultaneously. The same comparison star as at CAO was used. The transformation of magnitudes and colours to the standard Johnson photometric system has been well established for normal stars using the data from the channels 1, 3, 4 and 6 for the UBV and R pass-bands, respectively.

The correction for instrumental polarization was done by the observations of nonpolarized stars listed by Serkowski (1973). The zero-point of the polarization angle was determined by assuming a polarization angle of 170°(at the V pass-band) for the highly polarized star 9 Geminorum. The efficiency correction was made by inserting a quartz polarizer in front of a rotating achromatic half-wave plate, which modulates the signals with 20 Hz, followed by a Wallaston prism.

The total number of observational nights is 36. The results of the Dodaira photo-polarimetric observations of RR Tau are listed in Table 2.

3. Results

Before starting the analysis of the observational data we should take into account that RR Tau is associated with a weak S-shaped reflecting nebulosity (Herbig 1960). In this connection it is important to estimate what the influence of the nebulosity is on the background radiation. Moreover, the radiation of such nebulae is usually polarized and contributes in some cases appreciably to the intrinsic polarization of young stars (Vrba et al. 1979). To estimate the possible influence of the associated nebulosity we have observed RR Tau during moonless nights through two diaphragms: 10″and 20″. A comparison of these polarimetric measurements shows that they agree within the observational errors. We have estimated that the maximum of the background radiation through the 20″diaphragm is 17^m at the V pass-band. This means that the background radiation is negligible compared to the stellar flux over the whole range of the brightness variations of RR Tau and can, therefore, be neglected both in the polarimetric and photometric measurements.

[1] "Isolated" means not associated with nebulosity

[2] Preliminary results of these observations were presented at the First Conference on "The Nature and Evolutionary Status of the Herbig Ae/Be Stars" Amsterdam, October 1993.

[3] Tables 1 and 2 are presented in electronic form only and are available by ftp 130.79.128.5 from the CDS

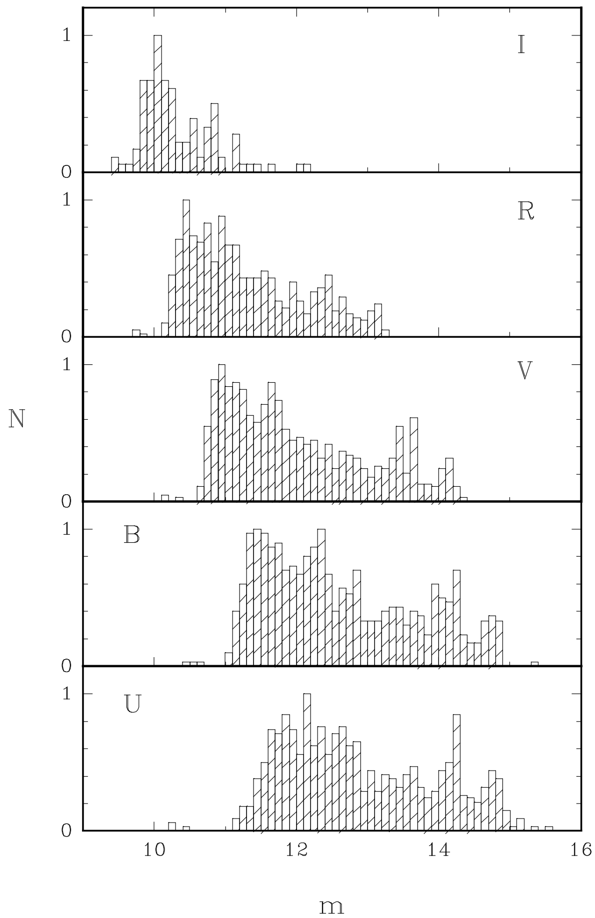

Fig. 1. Normalized histograms of the photometric activity of RR Tau in the $UBVRI$ pass-bands based on published data and data of the present paper. See text for details.

3.1. The photometric activity of RR Tau

The $UBVRI$ histograms presented in Fig. 1 give a general notion of the photometric activity of RR Tau. They are based on the following data: 46 UBV points by Zajtseva & Lyuty (1979), 45 $UBVR$ points by Shaimieva & Shutiomova (1985), 17 $UBVR$ points by Kardopolov & Rspaev (1989), 372 $UBVR$ points from Herbst et al.'s (1994) catalogue and 80 $UBVRI$ + 36 $UBVR$ points from Tables 1 and 2 of the present paper. Each point corresponds to one observation per night. In those cases when a few measurements were made during one night we have used the average value of the stellar magnitudes. The general asymmetry of the RR Tau activity histograms is typical for stars with non-periodic Algol-type minima (Parenago 1954).

In Fig. 2 we show the variations of the RR Tau stellar magnitudes, the degree and position angle of the linear polarization in the V pass-band based on data of the present paper. One can see from this figure that the observations at CAO and at Dodaira complement each other well. A comparison of photometric data obtained at the same nights at CAO and Dodaira shows no significant differences. As we have noted above RR Tau has a very large amplitude of variability: $V = 10\overset{\mathrm{m}}{.}2 - 14\overset{\mathrm{m}}{.}3$. Sometimes its magnitude changed rather rapidly from night to night. The maximum rate of brightness variability was registered on J.D. 8948/8949 to be 1^m per day at the V pass-band (here and below the initial part (244) of the Julian date is omitted).

During the observations we have registered when the star is both at its brightest and at its faintest states. The brightest states were observed on J.D. = 9224.5, 9225.6 and 9245.5 (Fig. 2). These three points are well above the values observed at any other given time (Fig. 1) and suggest the occurance of flares. The amplitude of the variation with respect to the "normal bright state (V=$10\overset{\mathrm{m}}{.}86$)" is the same in the two epochs:

J.D. = 9225: ΔU = 1.37, ΔB = 0.82, ΔV = 0.67, ΔR = 0.59, ΔI = 0.44

J.D. = 9245: ΔU = 1.35, ΔB = 0.87, ΔV = 0.71, ΔR = 0.60, ΔI = 0.44

The flare-like events at the light curve of RR Tau can also be seen in Fig. 1 of the paper by Zajtseva & Lyuty (1979). However, Goransky (1995) whose data were used in that light curve did not confirm the reality of that "flare". Analysis of the AAVSO long-term (from 1926 to 1958) observations collected by Mayer (1982) shows that such "flares" are very rare events, and have been observed only few times in all previous observations of RR Tau.

The deepest minimum of brightness of RR Tau (V = $14\overset{\mathrm{m}}{.}2$) has been observed at J.D. = 9372.24 at the Dodaira Observatory. The accuracy of the measurements at that night was quite low due to poor seeing conditions (the star was observed at a zenith angle of about 70°): about $0\overset{\mathrm{m}}{.}10$ in V and about $0\overset{\mathrm{m}}{.}17$, $0\overset{\mathrm{m}}{.}10$ and $0\overset{\mathrm{m}}{.}06$ in the colours $U-B$, $B-V$ and $V-R$, respectively.

The colour-magnitude diagrams of RR Tau are given in Fig. 3. They demonstrate the complex behaviour of the colour-indices $U-B$ and $B-V$ with the changes of brightness. These are similar to those observed by Rössiger & Wenzel (1974), Zajtseva (1986) and Kardopolov & Rspaev (1989): the initial reddening of the star stops at some brightness level and the star becomes bluer again with further decrease of the visual flux. This "blueing effect" is one of the most interesting photometric properties of many UXORs. It is caused by the scattered radiation due to CS dust, which dominates in the blue region of the spectrum at the times of deep minima (Grinin 1986). If this radiation arises in a large CS volume [4] it has to be constant and will determine a natural limitation to the amplitudes of Algol-type minima.

Using the upper (rectilinear) parts of the colour-magnitude diagrams we have estimated from the reddening of RR Tau the extinction law in the CS dust clouds revolving around this star: $R = \Delta V/\Delta(B-V)$ = 4.4. This value is larger than the mean value of the interstellar (IS) reddening (R = 3.0 - 3.2), which indicates that the grain sizes in the CS clouds are larger compared to those in the IS matter (see also Sect. 4).

[4] There are indications (Grinin 1994) that the part of the scattered radiation due to dust in the immediate vicinity of the star can be variable.

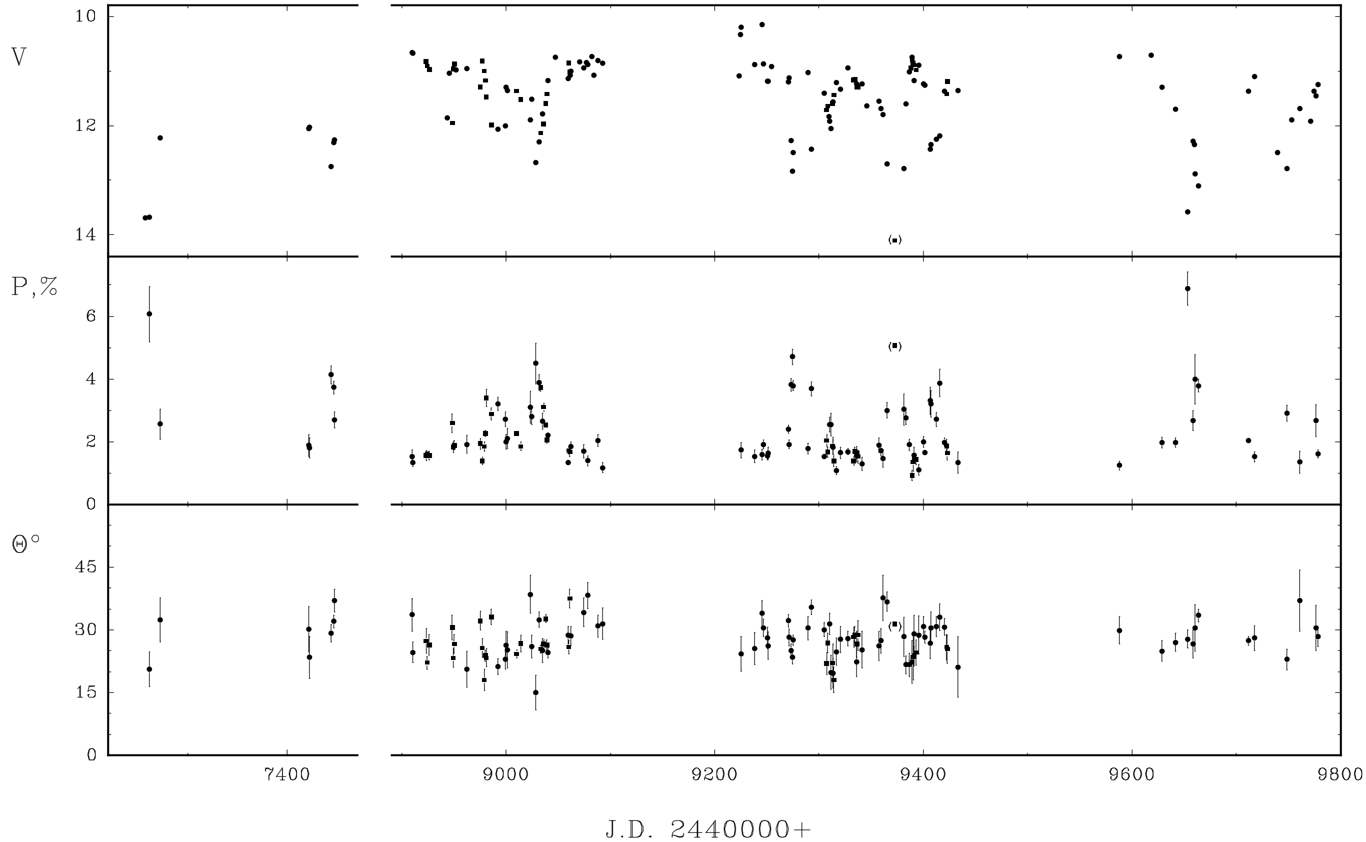

Fig. 2. Variations of the RR Tau stellar magnitude, the degree and position angle of the linear polarization at the V pass-band based on data of the present paper. Circles represent Crimean data, and squares those obtained at Dodaira.

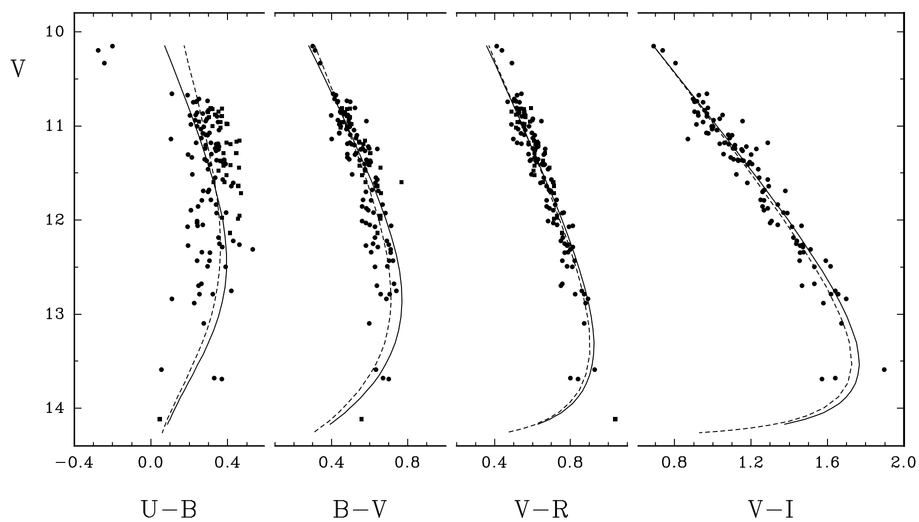

Fig. 3. The RR Tau colour-magnitude diagrams based on data in Tables 1 and 2. The meaning of the symbols is the same as in Fig. 2. The model fits are shown by solid (model 1) and dashed (model 2) lines (see text for more details).

3.2. The polarimetric activity of RR Tau

The brightness variations of RR Tau at all $UBVRI$ pass-bands were accompanied by significant changes of the polarization parameters. The anti-correlation between the degree of linear polarization and the stellar brightness is clearly seen in Figs. 2 and 5. The maximum degree of polarization in the V pass-band (P= 6.89 ± 0.53% with θ = 27.8 ± 2.2°) has been observed on J.D. 9653.4 when the star was at a deep minimum. Another deep minimum was observed near J.D. 9372.2 (Fig. 2). However due to poor seeing conditions the accuracy of the measurements on that night was low, therefore, we did not use them in our analysis.

Despite the strong variations of the degree of linear polarization observed during the deep minimum at J.D. 9653, the position angle did not change significantly. Since the observed

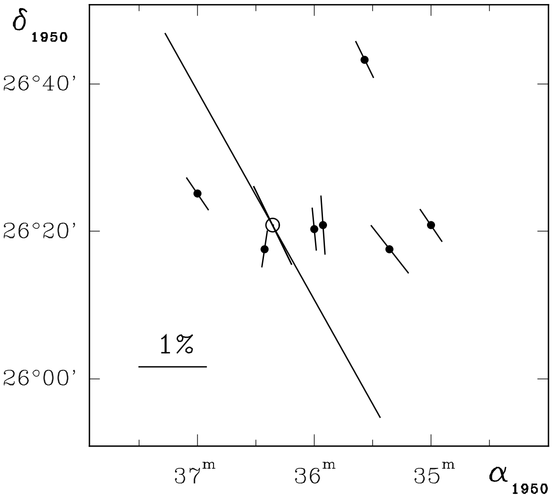

Fig. 4. Polarization map of the RR Tau neighbourhood based on the data of Shakhovskaya et al.'s (1986) paper. The observed polarization of RR Tau itself (open circle) is given for the normal state of the star and for the deep minimum.

polarization is the sum of the variable intrinsic component and the constant component of the IS matter, this means that the position angles of both components are about the same. This suggestion is supported by the polarization map of the region around RR Tau (Fig. 4): the mean value of the position angle of the IS polarization in this region is: θ_{IS} = 17° which coincides within about 10° with the position angle of the polarization of RR Tau at deep minimum.

From Fig. 5 one can see that the dependence of the percentage of the observed polarization at all five pass-bands on the stellar magnitudes is *non-linear* and agrees well with those determined theoretically using the model of CS screening, explained below. A comparison with the data of Kardopolov and Rspaev (1989) shows that they agree well with our data observed at the same brightness of the star. This means that the Stokes parameters of the radiation scattered in the CS dust envelope of RR Tau did not change significantly within the time interval of about 7 years. It is interesting to note also that according to Figs. 2 and 5 the intrinsic polarization of the star did not change during the flare-like events which were observed near J.D. 9224 and 9245.

The wavelength dependences of the RR Tau linear polarization observed at different levels of its brightness are shown in Fig. 6. They resemble those observed in another UXOR WW Vul (see Fig. 2 in the paper by Grinin et al. 1988). Such a behaviour of P_λ is the result of selective weakening of the direct (non-polarized) stellar radiation in the sum of the radiation of the star and the CS dust.

Fig. 7 shows the behaviour of the Stokes parameters of the RR Tau radiation at the V pass-band in the P_x, P_y plane. At the bright state of the star the intrinsic polarization is small and the observed polarization is determined almost completely by the interstellar component (see below). At the deep minima it is almost entirely caused by scattered radiation in the CS dust envelope.

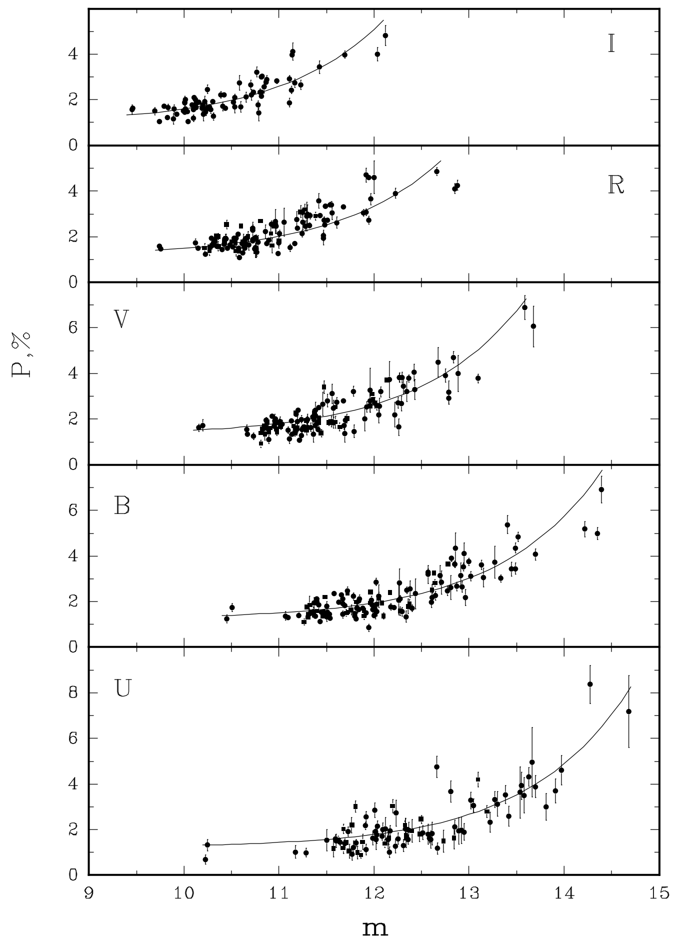

Fig. 5. RR Tau polarization degree vs. $UBVRI$ magnitudes. The solid lines show the theoretical dependence $P(\Delta m)$ from Eqs. 2-3. Symbols as in Fig. 2

4. Discussion

A comparison of RR Tau with other stars of this subclass (see Grinin et al. 1991 and references therein) shows that its photopolarimetric behaviour is similar to that of the other UXORs and agrees well with the variable circumstellar extinction model suggested by Grinin (1986), in which the scattered radiation of the CS dust changes the colour indices and Stokes parameters of the total radiation of the central star and its CS disk, at the times of occurrence of the Algol-type minima.

In the framework of this model the brightest state of the star corresponds to its intrinsic luminosity. On the other hand we have observed in RR Tau two unusual events resembling flares. Such events seems to be incompatible with the considered model, which is based on variable CS extinction. Let us consider briefly what their origin possibly can be.

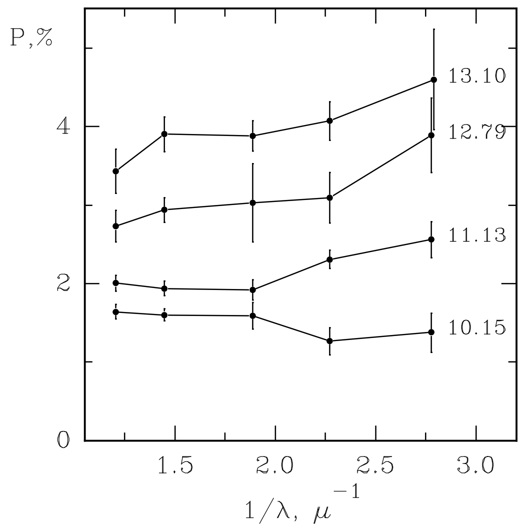

Fig. 6. The wavelength dependence of the linear polarization of RR Tau for the different V stellar magnitudes.

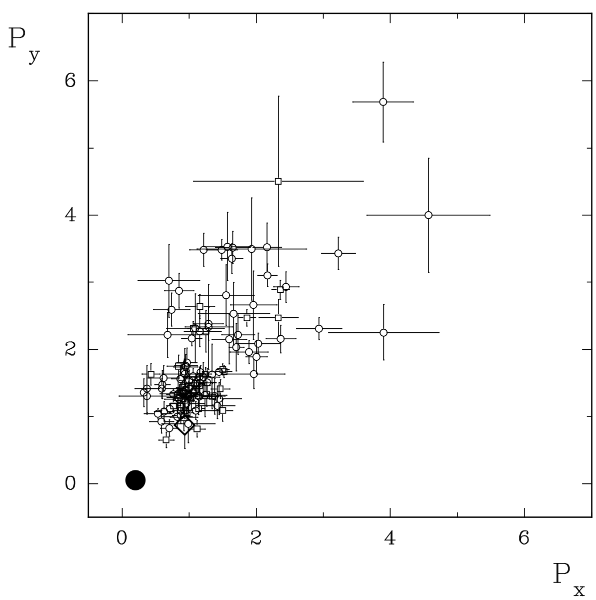

Fig. 7. Behavior of the parameters P_x and P_y of the polarization of RR Tau in the V pass-band. Open dots are Crimean data, open squares are Dodaira data. For reference, we show the values of the IS component (◇) and the intrinsic component of linear polarization (•) of the star in the brightest state (V = $10\overset{\rm m}{.}153$) from Table 3.

4.1. ”Flares” of RR Tau

An overview of the published photometric observations of HAeBe stars shows that “flares” similar to those observed in RR Tau near J.D. 9224 and 9245 (Fig. 2) are not common. Other flares have been observed in the HAeBe stars V351 Ori by Koval’chuk (1984), in HR 5999 by Pérez et al. (1992) and in BF Ori by Koval’chuk & Pugach (1991). Moreover, a short “outburst” of the HAeBe star V1686 Cyg is shown in Fig. 2.13 of Shevchenko’s (1989) book.

According to Fig. 3 during both “flares” of RR Tau the colour indices $B-V$, $V-R$ and $V-I$ changed along lines which continue the upper parts of the colour-magnitude diagrams. The same is true also for the flare event of BF Ori observed by Koval’chuk & Pugach (1991). This means that the flare-like events can be interpreted as the result of *the decrease of dust extinction in the line-of-sight due to formation of short-living (few days) “holes” free (or almost free) of dust* in the neighbourhood of the star.

Formation of such holes was probably accompanied by the local heating of CS matter and the formation of additional gas emission. This suggestion follows from the behaviour of the colour index $U-B$. According to Fig. 3 both flares of RR Tau are very blue: $U-B \simeq$ - $0\overset{\rm m}{.}40$ which is typical for the case when the hydrogen bound-free emission beyond the Balmer jump begins to dominate. If so, the radiation of RR Tau during the “flares” is not purely photospheric one but includes also some additional hydrogen emission.

A more detailed discussion of the “flares” in RR Tau and other UXORs is beyond the scope of the present paper and will be made somewhere else.

4.2. The energy distribution of RR Tau

Using the colour index $B-V$ = $0\overset{\rm m}{.}30$ at the brightest state of RR Tau and the “normal” IS extinction law (R = 3.1) we estimated: A_V = $1\overset{\rm m}{.}2$ if the spectral type of the star is B8, and A_V = $0\overset{\rm m}{.}60$ for the spectral type A3. Two energy distributions based on the above estimated values of A_V are shown in Fig. 8. In both cases we have used the brightest $UBVRI$ points from Table 1, the IR data for 12, 25 and 60 μm from the IRAS catalog (Gezari et al. 1987), and the JHKLMN magnitudes from Hillenbrand et al.’s (1992) paper. The energy distributions in the UV part of the spectrum were taken from Kurucz’s (1992) models for T_{eff} = 13500 K (B8), and T_{eff} = 9400 K (A3) and log g = 3. On the basis of these data we have estimated the ratios of the IR excess to the bolometric luminosity of RR Tau L_{IR}/L_* to be 0.17 and 0.40, correspondingly. The last value seems to be more realistic since when estimating the spectral type of RR Tau (A3-A5) Strom et al. (1972) used the profiles of the photosperic Balmer lines $H\gamma$ and $H\delta$.

4.3. The scattered radiation and the screening effect

According to the considered model (see Subsection 4.1), the scattered radiation of the protoplanetary disk, which is responsible for the change in the observed colours and linear polarization of a star during Algol-type minima, restricts the variation amplitude as well: they cannot exceed the value

$$(\Delta m)_{max} = 2.5 \log(1 + I_*/I_{sc}) \quad (1)$$

where I_* and I_{sc} are the intensities of the direct and scattered radiation at the given wavelength, respectively.

In the case of the photometrically most active UXORs the amplitudes of the deepest minima do not usually exceed 2 -

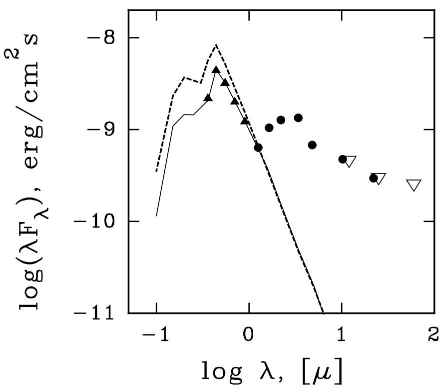

Fig. 8. The energy distributions of RR Tau. The solid line corresponds to the spectral type A3, dashed line to B8. The filled triangles up are the $UBVRI$ points, the filled circles are the $JHKLMN$ magnitudes, triangles down are the IR data from IRAS catalog. See text for more details.

3 stellar magnitudes in the V band (Herbst 1986), which corresponds to the intensity of the scattered light in units of the stellar bolometric luminosity: $I_{sc}/I_* \simeq 0.10$ (Grinin 1986). In the case of RR Tau the observed amplitudes of the deepest minima are about 4^m in the V band (see Fig. 1), which corresponds to the ratio $I_{sc}/I_* \simeq 0.03$. This simple estimate shows that the scattered radiation of the CS dust envelope of RR Tau is fainter compared with that of other UXORs.

In order to separate the intrinsic linear polarization of RR Tau, caused by scattered radiation, from that due to the IS matter, we assume here (following our previous papers) that the Stokes parameters of the scattered radiation had not changed significantly during the considered time interval of about 7 years. The observational evidence supporting this assumption is discussed in the previous section.

In this case the linear polarization at any given wavelength must change with an amplitude of the brightness variation at the same wavelength (Δm) as:

$$\boldsymbol{P}_{obs}(\Delta m) = \boldsymbol{P}_{is} + \boldsymbol{P}_{in}(\Delta m) \quad (2)$$

where

$$P_{in}(\Delta m) = P_{in}(0) \cdot 10^{0.4\Delta m}. \quad (3)$$

Here $\boldsymbol{P}_{is}$ is the interstellar polarization of RR Tau, and $\boldsymbol{P}_{in}(0)$ represents the intrinsic polarization at the maximum brightness state of the star, whereas Δm is the amplitude of the brightness variation from this brightest state.

Using (2) and (3) one can answer the questions:

1. is the intrinsic polarization indeed caused by scattering in the non-spherical CS dust envelope; and
2. are the brightness variations of the star caused by the screening effect?

Rewriting Eqs. (2) and (3) for Stokes parameters P_x, P_y and putting in the left side of Eq. (2) the Stokes parameters of RR Tau observed at the different brightness states we can transform these equations into a system of linear algebraic equations. Each equation of this system corresponds to one observation in one pass-band. The unknown values are the Stokes parameters of the intrinsic linear polarization at the brightest state and the IS component. The system of equations so obtained, were then solved for each pass-band applying the least squares method taking into account the weight of each observation. The calculated parameters of the IS and the intrinsic linear polarization of RR Tau are given in Table 3 and depicted in Figs. 5 and 9.

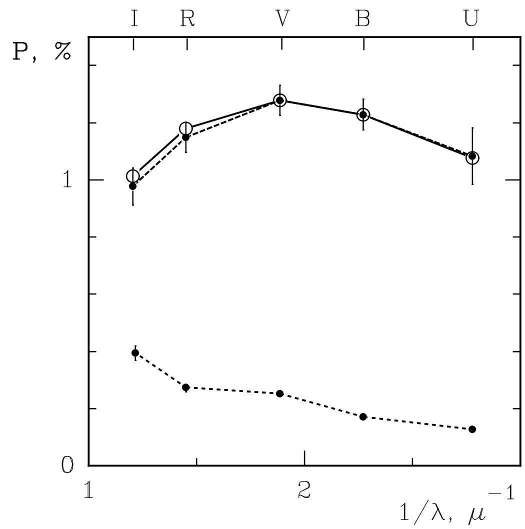

Fig. 9. The wavelength dependence of RR Tau's intrinsic linear polarization at the bright state $P_{in}(0)$ (lower curve) and the IS polarization P_{is} (upper curve), calculated using Eq. (1); the open circles and the connecting solid line give the wavelength dependence of the IS polarization according to Serkowski's law.

Table 3. The intrinsic and interstellar components of the RR Tau's linear polarization.

Fil.	P_{is} [%]	σ [%]	θP_{is} [°]	σ [°]	P_{in} [%]	σ [%]	θP_{in} [°]	σ [°]
U	1.08	0.10	29.4	2.6	0.13	0.01	21.0	3.0
B	1.23	0.05	26.3	1.3	0.17	0.01	26.9	1.8
V	1.28	0.05	21.7	1.2	0.25	0.02	29.8	1.7
R	1.15	0.05	27.9	1.3	0.27	0.02	29.0	1.7
I	0.98	0.06	34.0	1.9	0.39	0.03	26.3	1.8

We see from Table 3 that: i) the accuracy of both calculated components of the linear polarization is quite high (except perhaps at the U pass-band in which the flare-like events were only partially caused by variations of the CS extinction), ii) the position angles of P_{in} coincide within a 3σ interval in all five pass-bands; the same is also true for the IS component. Since the above described method has been made independently for each pass-band such a coincidence of θ indicates that the separation of the IS and the intrinsic components from the observed po-

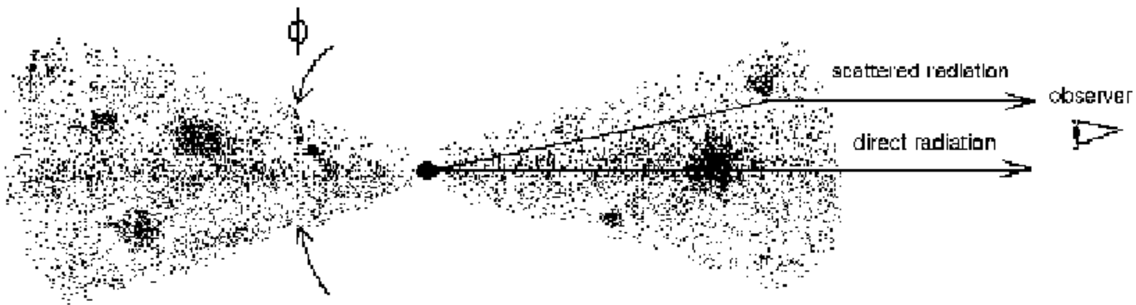

Fig. 10. Schematic picture of the Algol-type minimum of an UXOR according to Grinin's (1986) model. The CS dust cloud which intersects the line-of-sight acts as a natural coronograph. In the deep minimum, when the direct stellar radiation is blocked, the faint scattered radiation of the proto-planetary disk dominates.

larization of RR Tau was correct. The wavelength dependence of the IS polarization confirms this suggestion (Fig. 9): it practically coincides with Serkowski's law, with P_{max} and λ_{max} taken from Table 3.

According to Fig. 5 the calculated degrees of polarizations using Eqs. (2), (3) and the theoretical dependence of the total polarization of the star on the stellar magnitude agrees well in all five pass-bands with the observed ones, within the observed variability ranges of RR Tau. This confirms our assumption that the screening effect is the main source of the large-scale irregular variability of RR Tau. At the same time the dispersion of the observational points from the theoretical lines in Fig. 5 can be quite large and cannot be explained by observational errors. A possible mechanism for these deviations (which are also observed in other UXORs) was discussed in a review paper by Grinin (1994). It can be caused by dust formation due to the disintegration of star-grazing planetesimal bodies in the vicinity of a star (see also Grinin et al. 1996).

4.4. Circumstellar dust modeling

Simultaneous multi-band photometric and polarimetric observations of UXORs at different brightness states of the stars including deep minima, are a good basis for modeling the dust envelopes surrounding these stars. Their preferential orientation (edge-on) relative to the line-of-sight simplified the numerical simulations substantially, since it permits to avoid the uncertainty in the linear polarization degree proportional to $sin^2 i$ connected with the orientation of the envelope relative to the plane of the sky, which is usually unknown.

The model considered below consists of two elements:

a) The dust cloud intersecting the line-of-sight. Its optical properties determine the initial reddening of the star and depend on the parameters of the dust mixture. By increasing the optical thickness of the cloud we can simulate the Algol-type minima.

b) The optical parameters of the dust envelope which scatter the radiation of the central star are assumed to be constant. They determined the "turnaround" observed in the colour-magnitude diagrams.

We have used for the calculation the Mie theory and the Monte Carlo numerical code described by Voshchinnikov and Karjukin (1994). We have changed in this code the envelope geometry. Instead of the spheroidal form we have used the simplified model of the CS envelope presented schematically in Fig. 10. Such a model agrees better with the classical model of accretion disks (Shakura and Sunyaev 1973). We have assumed for simplicity that the CS dust envelope is homogeneous and that the dust mixtures are the same both in the envelope and in the dust cloud which intersects the line-of-sight.

The model parameters are:

a) *The dust parameters*. As in the paper by Voshchinnikov et al. (1988) we used here a dust mixture of graphite and silicate particles having the same the size distributions:

$$n(a) \sim a^{-q} \qquad a_{max} \geq a \geq a_{min} \qquad (4)$$

where q, a_{min}, a_{max} and the ratio of silicate to graphite particles Si/C are the model parameters.

b) *The envelope parameters*. These are the opening angle ϕ (see Fig. 10) and the optical thickness in the equatorial plane in the U band: τ_U.

A few tens of models of the CS dust envelopes for different combinations of the model parameters were calculated and were compared with the observational data. The best fit to the observed colour-magnitude diagrams and the wavelength dependence of the intrinsic linear polarization of RR Tau, $P_{in}(\lambda)$, is found for two models with slightly different parameters:

- Model 1: a_{min} = 0.040μm, ϕ = 14°
- Model 2: a_{min} = 0.055μm, ϕ = 13°

The other parameters in both models are the same: a_{max} = 0.25μm, q = 3.5, τ_U = 2.2, and Si/C = 1.07 (such as in the case of the IS medium (see Mathis et al. 1977)).

The results of the numerical simulation of the Algol-type minima based on these models are depicted in Figs. 3 and 11. The first model describes the wavelength dependence of the intrinsic linear polarization of RR Tau (Fig. 11) better. The second one explains better the initial reddening in the observed colour-magnitude diagrams of the star (Fig. 3) excluding the "flares" in the U band (see above).

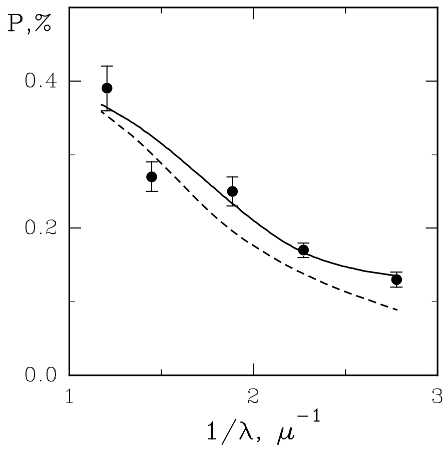

Fig. 11. The best theoretical fit of RR Tau's intrinsic linear polarization in the brightest state. Model 1 (solid) and model 2 (dashed) are the same as in the colour-magnitude diagrams of RR Tau in Fig. 3.

4.5. Comparison with other objects

In both cases the CS dust mixture is similar to that of the IS matter (Mathis et al. 1977) but differs from it in the minimum size of the particles: in the mixture of the IS dust applied by Mathis et al. (1977) the value of a_{min} = 0.005μm, whereas in the above presented models these parameters are *about ten times larger*. Similar conclusions was reached earlier in the numerical simulations of the Algol-type minima observed in two other UXORs: UX Ori itself and WW Vul (Voshchinnikov et al. 1988, 1995). It is of interest to mention here, that the same larger minimum size of dust particles in the circumstellar disk of pre-main sequence stars was also found in the study of the extinction law in the direction of such stars by Steenman and Thé (1989, 1991).

The above result can be considered as evidence that the growth of particles has already begun in the young protoplanetary disk of RR Tau, but that the particles are still smaller then in the "old" protoplanetary disks of Vega-like stars (Chini et al. 1990) including β Pictoris (Paresce and Burrows, 1987; Telesko and Knacke, 1991).

5. Conclusion

The main results obtained in this work can be summarized as follows:

1. The anti-correlation between the linear polarization and the brightness variations of the classical HAeBe star RR Tau, observed earlier by Kardopolov and Rspaev (1989) and Kardopolov et al. (1994), is confirmed in the larger interval of brightness changes, which cover practically all the observed variability range (about 100 times in the U pass-band!). Such a behaviour agrees well with the predicted results in the model of variable CS screening of a young star, in which the opaque dust fragments of its protoplanetary disk are causing this effect.

2. In the framework of this model the minimum of the brightness variations are controlled by scattered radiation due to CS dust, which dominates at deep minima. In the case of RR Tau this radiation is weaker compared with other UXORs; it is only about 3% of the stellar radiation in the V pass-band.

3. The position angle of the intrinsic linear polarization of RR Tau coincides within about 10° with the direction of the local magnetic field estimated from the polarization map of this region. Such a coincidence means that the equatorial plane of the circumstellar disk-like envelope of RR Tau is perpendicular to the magnetic lines. A similar feature was found earlier for several other UXORs: (Grinin et al. 1988, 1991, 1995). From the point of view of the modern scenario of star formation (see Mestel 1985) such an orientation indicates an important rôle of the magnetic field at the initial phase of collapse of the protostellar cloud.

4. Two flare-like events of RR Tau were observed near J.D. 9224-9225 and 9245. The colour-magnitude variations during both "flares" follows with similar slopes the upper parts of the colour-magnitude diagrams of RR Tau $(B-V)$ vs. V, $(V-R)$ vs. V and $(V-I)$ vs. V caused by CS reddening. This means that both "flares" were caused by the occurrence of short-living holes, almost free of dust, in the line-of-sight. However, such an interpretation does not explain the blue colour $U-B$ of the "flares" which is probably connected with Balmer jump emission. Both these phenomena: formation of the short-living holes free of dust and the additional hydrogen emission are probably different manifestations of the same phenomenon connected with violent non-stationary processes in the neighbourhood of the star.

5. The numerical simulation of the colour-magnitude diagrams and the intrinsic linear polarization of RR Tau based on the Mie theory support our previous conclusion (Grinin et al. 1991) that the CS dust envelopes around UXORs are *strongly flattened*. This result is important in the light of current discussions of models of CS envelopes around HAeBe stars (see Hartmann et al. 1993 and references therein). It means that the geometry of the dust envelopes of these stars (many of them are HAeBe stars) does not differ principally from those of T Tauri stars. Their form is disk-like.

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