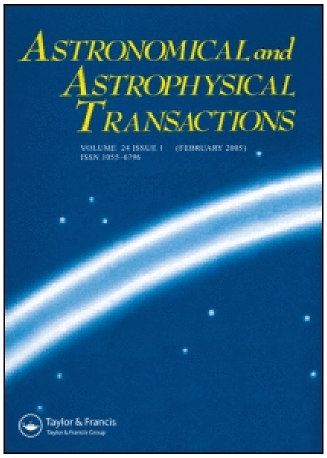

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YOUNG STARS WITH NON-PERIODIC ALGOL-TYPE MINIMA†

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The irregular variability is one of the most important properties of young stellar objects and is of great interest since its understanding is the key to understanding the physics of young stars. The main question is: how to separate, in each concrete case, the different potentially important mechanisms of the variability, such as the variable circumstellar extinction, the flare (and chromospheric) activity, and the suppression of stellar photosphere by the formation of magnetic spots? We consider this question below in application to an interesting subclass of young stars, the stars with non-periodic Algol-type minima. The most important results of current investigations of these stars are discussed.

KEY WORDS Protoplanetary disks, variable observation, variability of young stars.

1. INTRODUCTION

The stars with non-periodic Algol-type minima were selected as an individual subclass in the pioneering works by Hoffmeister (1949), Parenago (1954), Wenzel (1957) and Kholopov (1959). At the present time, this subclass includes a few tens objects, many of which belong to the Orion population of stars (Herbig and Bell 1989). Among them are Ae/Be Herbig stars, T Tauri stars and some stars with unclear evolutionary status.

These stars have infrared (IR) excess because of the thermal radiation of circumstellar (CS) dust (Cohen, 1973; Glass and Penston, 1973), and the decrease of their brightness is usually accompanied by their reddening. Therefore, Wenzel's (1968) idea that the Algol-type minima are due to the existence of protoplanetary clouds around these stars and variable obscuration of those by inhomogeneous CS matter was supported by many astronomers (see, e.g., Gham, 1974; Walker, 1978, 1980; Tjin A Dje *et al.*, 1984).

However, serious arguments against this interpretation were formulated in the mid-eighties and an alternative conception for the explanation of this phenomenon was suggested (Gershberg and Petrov, 1976; Herbst *et al.*, 1983; Rydgren and Cohen, 1985; Herbst, 1986). According to the new conception (supported in the theoretical work by Appenzeller and Dearborn, 1984), the sporadic minima of young stars are due to their violent magnetic activity and the reddening of stars in the minima is a result of the temperature variations on the stellar surface.

† The paper presented at the Astronomical Conference "Astrophysics Today", Nizhnij Novgorod, March, 1991.

What were these arguments?

i) "Why, if variable obscuration is involved, are the brightness excursions limited to about 2 magnitudes? If dust could make the star fade by 2 magnitudes, why not 5 or even 10 magnitudes sometimes?" (Herbst, 1986).

ii) "If the changing of CS obscuration is responsible for larger-amplitude variation in these stars, this would imply that the dust is not confined to a thin disc structure, because we should not be seeing all these stars exactly equator-on" (Rydgren and Cohen, 1985). On the other hand, there is ample observational and theoretical evidence showing that CS disks are an important common property of young stellar objects (Strom, 1985).

iii) Finally, in the framework of the variable CS extinction model it was not simple to explain the unusual behavior of colors on the color/magnitude diagram (see below) and the systematic dependence of colors and H_α emission on V magnitude. According to Rydgren and Cohen (1985), such dependence "... is incompatible with variable circumstellar obscuration and implies that these large-amplitude brightness variations originate in the star itself".

The aforementioned difficulties of the variable CS extinction model were the decisive argument in favor of the surface magnetic activity of young stars as a main source of their photometric and spectroscopic activity.

2. THE PRESENT SITUATION

Recently, we have found simple answers to these questions (see Grinin *et al.*, 1991 and references therein) and have proved that:

i) The nature of the Algol-type minima in these stars is actually due to rotating proplanetary disks. That is to say, Wenzel's idea is correct.

ii) Indeed, the photometrically active stars of this subclass have the CS disks seen edge-on or having small inclination to the line of sight.

iii) The problem with the interpretation of the unusual behavior of colors in the deep minima of these stars has most natural solution in the framework of the variable circumstellar extinction model.

a) *How it was made*?

In 1986 we started the investigation of one nontrivial feature of these stars, which has been first discovered by Götz and Wenzel (1969). Observing one of the stars of this subclass (CQ Tau) in the deep minima they have found that, beginning from some brightness level, the reddening of the star is stopped and its $U{-}B$ and $B{-}V$ colors become bluer again with further decrease in the visual flux. Subsequently, the same "turn-around" of $U-B$ and $B-V$ colors has been observed by Zaitseva (1973) in the deep minima of UX Ori. To the present time, this effect has been observed in many stars of this subclass and this is one of the more important properties of their photometric behavior (Herbst, 1986; see also Figures 1 and 10).

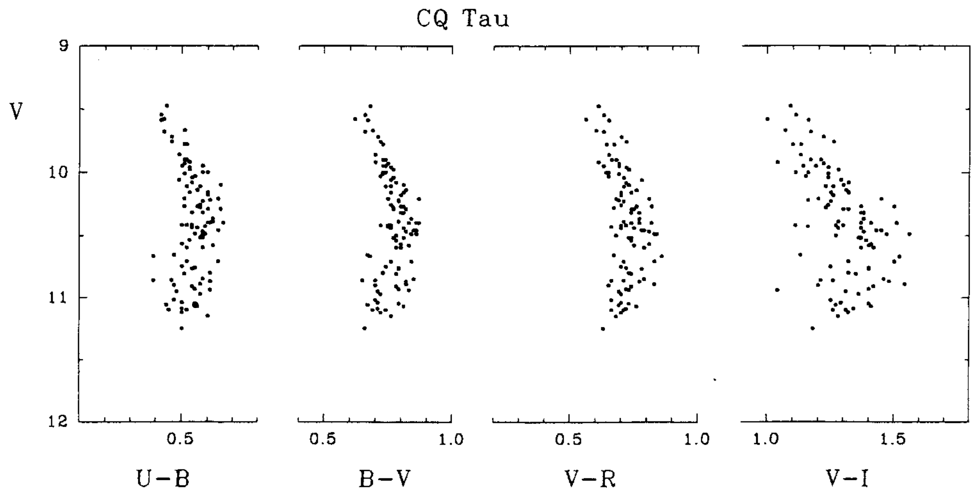

Figure 1a The color-magnitude diagrams of the isolated Ae Herbig star CQ Tau based on Crimean observations in 1988–90 (Berdjugin *et al.*, 1990).

This effect played an important role in the assertion of the conception mentioned above, according to which the star weakening is a result of a violent formation of large magnetic spots on their surface. In the framework of this conception, the source of the blue emission (strengthening in the deep minima) is the radiation of active regions above the spots (Rydgren and Cohen, 1985; Herbst, 1986; Hoffmeister *et al.*, 1987). As a direct evidence in favor of such an interpretation, the spectral observations by Kolotilov (1977) were invoked: he has

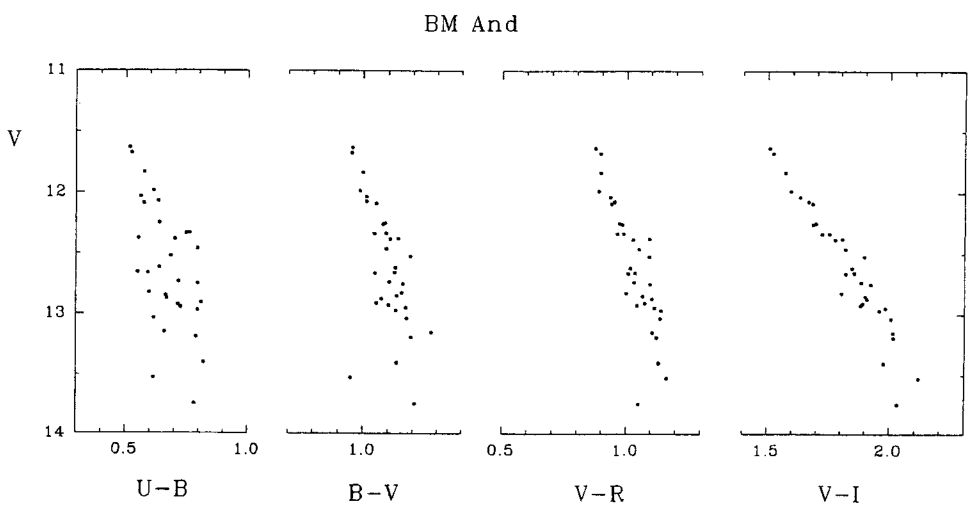

Figure 1b The color-magnitude diagrams of the classical T Tauri type star BM And based on Crimean observations in 1990–1991 (Grinin *et al.*, 1991). The "turn-around" of the (U−B) color is quite weak for this star.

shown that the equivalent width of the H_α emission line increases in the minima of UX Ori, WW Vul and VX Cas, which directly implies an increasing contribution of the gas emission to the total radiation of the stars in the minima. This result was confirmed by Herbst *et al.* (1983), thus removing any doubts that the "blueing" effect is due to the radiation of active regions on the star surface.

According to the mechanism of violent magnetic activity, such an explanation seemed to be quite logical. Nevertheless, some doubts were raised soon by the present author (Grinin 1986) who noticed some "roughness" of this interpretation and proposed a new approach to the explanation of this phenomenon.

With this approach, the initial reddening of the stars in the minima is due to selective absorption of direct stellar radiation in the CS dust cloud intersecting the line of sight. Beginning from some level of brightness (different for the different stars), the weak scattered light formed at the scattering of stellar radiation by circumcloud dust (and by the ensemble of the dust clouds themselves, of course) begins to dominate. The latter causes the "turn-around" of colors tracks in the deep minima of these stars.

So, a new approach is based on the initial model by Wenzel and it differs from that in only one respect: it takes into account the scattered radiation of the protoplanetary disk which can be considered as a direct analogy of interplanetary zodiacal light.

This entails the following simple prediction: the scattered radiation should be polarized and, therefore, the linear polarization of the stars should increase in the minima. It is easy to show that the degree of linear polarization should be a simple function of the amplitude of brightness variations Δm:

$$\vec{P}_{\text{obs}}(\Delta m) = \vec{P}_{\text{is}} + \vec{P}_{\text{sc}}(0)10^{0.4\,\Delta m}, \tag{1}$$

where P_{is} is the interstellar (IS) polarization, $P_{\text{sc}}(0)$ is the intrinsic polarization of a star in the bright state ($\Delta m = 0$) due to the scattering of stellar radiation in the protoplanetary disk.

To check this observational test, patrol observations of linear polarization and brightness of these stars were started† in early 1986 at two observatories, in the Crimea (1.2 m telescope + photometer/polarimeter of Helsinki University—Piirola, 1975) and on the Sanglok (Tajikistan) 1 m telescope. A part of the observations of UX Ori were made in 1986 at the Soviet-Bolivian Observatory. The most important results of this program are as follows:

i) The predicted effect has been found up to now in about ten stars of this subclass. Among them are: six isolated Ae Herbig stars: UX Ori (Voshchinnikov *et al.*, 1988), WW Vul (Grinin *et al.*, 1988), BF Ori (Grinin *et al.*, 1989), CQ Tau (Berdjugin *et al.*, 1990), VX Cas (Rostopchina, 1991) and V586 Ori (Berdjugin, 1992);

—one classical T Tauri star BM And (Grinin *et al.*, 1991; see also Kardopolov and Raspaev, 1990);

—the irregular variable star RZ Psc (Kiselev *et al.*, 1991).

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† As a search of the literature has shown, polarization of these stars in the deep minima had not been observed to that time. For many typical examples (like UX Ori, WW Vul and CQ Tau), the linear polarization was not observed not only in the minima but in the bright state as well. In other words, it was one of the "white spots" in the observations of these stars.

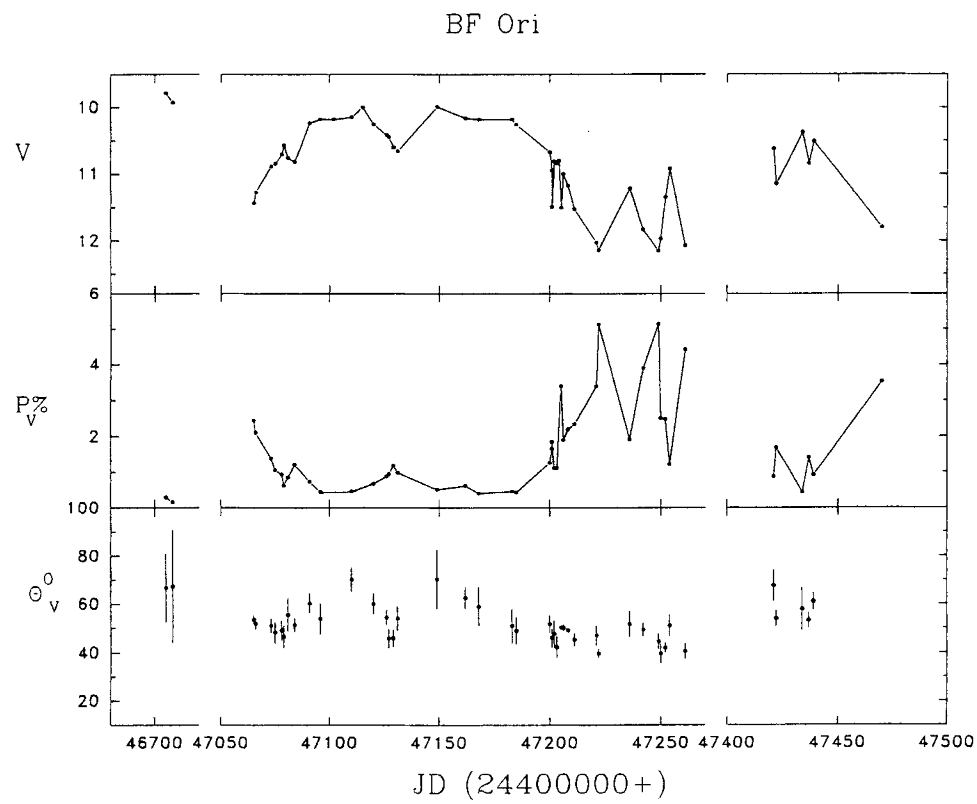


Figure 2 The behavior of the linear polarization and brightness of the Ae Herbig star BF Ori in the V band from Crimean and Sanglok observations of 1988–89 (Grinin *et al.*, 1989).

The strong changes of the linear polarization (up to 10 times!) have been observed for many of these stars (Figures 2–6 and 7).

ii) The amplitude of the brightness variations and the degree of observed linear polarization are in agreement with the law (1) (Figure 6). This fact and the form of P_λ wavelength dependence in the deep minima (Figures 8 and 9) are important arguments in favor of the assumption that the intrinsic polarization of these stars is mainly due to the scattered radiation by the protoplanetary disk.

Thus, a strong evidence has been found that the unusual behavior of the color tracks on the color/magnitude diagrams is explained fully by the CS dust and the larger contribution of hot gas emission in the minima does not affect the color of these stars.† This point of view has been supported recently by Kardopolov and Rspaev (1989) and Bibo and The (1990) and was recognized as the most natural one for the conditions in young stars.

† The increase of the contribution of the hot gas emission in the minima may arise because, when screening out the star, the dust clouds do not fully screen the more extended CS gas envelope (Zaitseva, 1973).

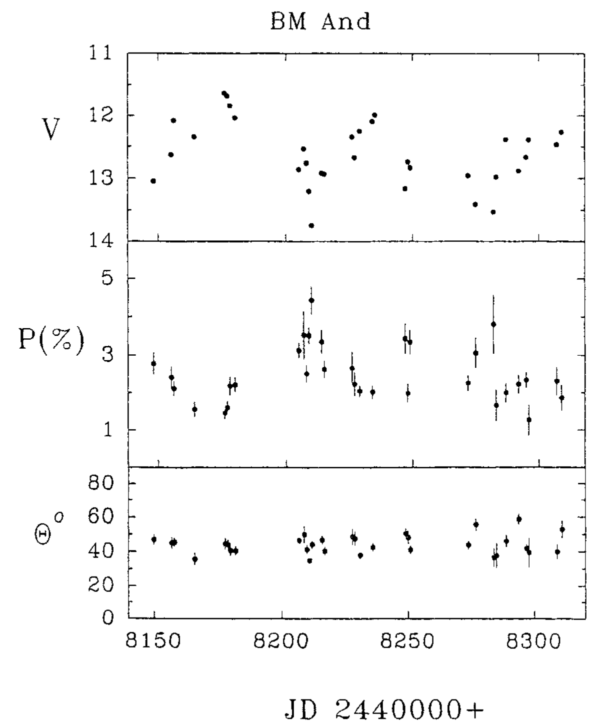


Figure 3 The behavior of the linear polarization and brightness of the classical T Tauri star BM And in the V band according to Crimean observations in 1990–91 (Grinin *et al.*, 1991).

So, we can answer the first question mentioned above: Why these stars never exhibit very deep minima with the amplitude 5^m or even 10^m? The answer is very simple: at the eclipse of a star by opaque dust clouds the total radiation flux of the system "star + scattering disk" cannot decrease below the level of the scattered light of the disk.

The answer to the second question was found after an analysis of the linear polarization of a number of the most photometrically active stars (like UX Ori, WW Vul, BF Ori, CQ Tau, etc.): it turned out that their intrinsic polarization in the deep minima is quite high (5–8%, see Figure 7) and it is necessary to assume that in all these cases the CS disks are seen edge-on. We concluded from this that at the very beginning, when Hoffmeister, Parenago, Wenzel and Kholopov singled out this subclass of stars, a strong selection effect was present. As a result, the stars seen equator-on were selected.

An additional argument supporting our assumption is the following: according to Finkenzeller and Mundt (1984), about 50% of Ae/Be Herbig stars have a two-component H_α profile which is usually interpreted as a result of rotation of a circumstellar gas. For our stars, we have found that such H_α profiles are observed almost in 100% cases! Since the gaseous and dust disks are probably coplanar, this is an additional observational fact in favor of the existence of a preferred orientation of CS disks around photometrically active young stars.

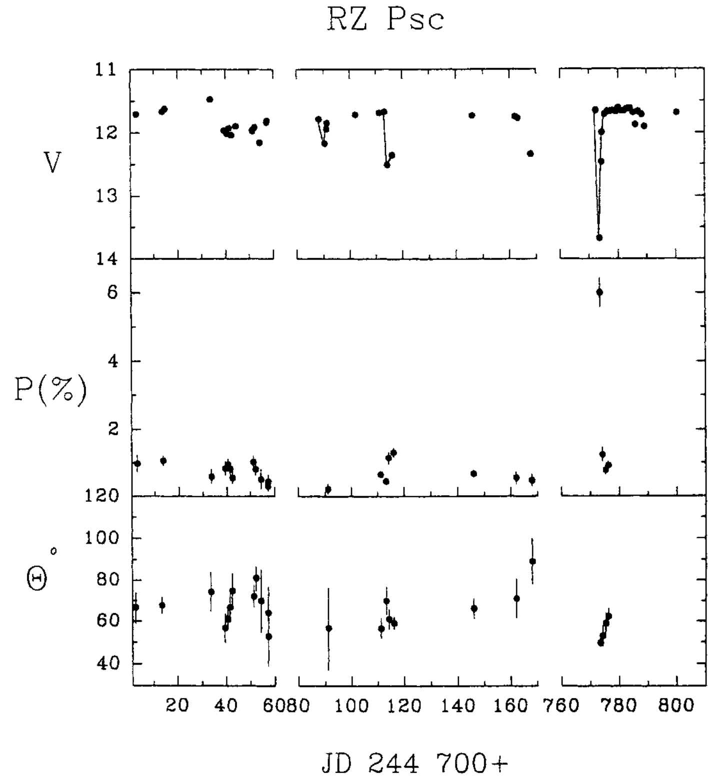


Figure 4 The "flare" of linear polarization in the deep minimum of RZ Psc according to Sanglok observations (Kiselev *et al.*, 1991).

Note: The evolutionary status of this star is not clear as yet. It has a weak IR excess, has no emission lines in the spectrum (Herbig, 1960), and lies far from regions of active star formation. The Algol-type minima are short and rare. We assume that this star is on its way to the β Pictoris stage.

Thus, if Rydgren and Cohen (1985) believe that the preferred orientation (edge-on) of the protoplanetary disks around photometrically active young stars is a nonsense, we say: on the contrary, these stars are known as irregular variables with Algol-type minima precisely due to such preferred orientation.

b) *What does this finding give?*

So, these stars provide a unique possibility to "look" in the remote past of our solar system and we can observe the formation of a planetary system around a young star in that most important phase when this process is still under way and fragments of the future planets are rotating around the star. The evidence of this is the main result of our program.

From the point of view of the observations, the stars with Algol-type minima are somewhat similar to the β Pictoris star: in both cases, the star should be screened out in order to observe the circumstellar disk. For β Pictoris, the

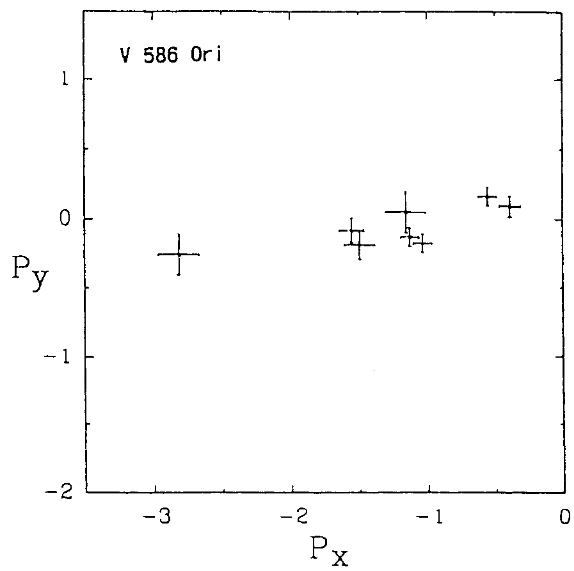


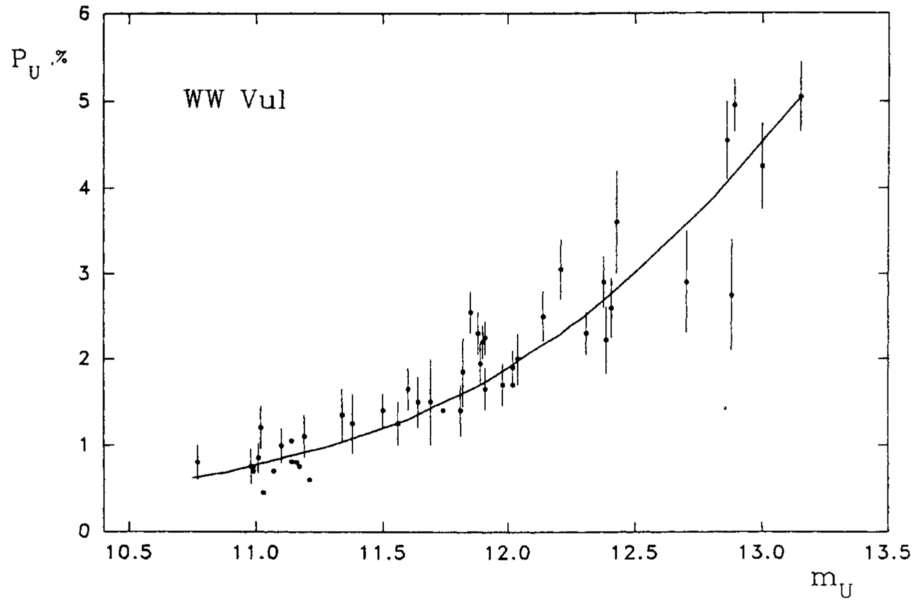
Figure 5 The variations of the parameters P_x and P_y of the linear polarization of Ae Herbig star V586 Ori in the R band from Berdjugin (1992). The decrease of brightness is accompanied by the increase of the linear polarization degree (which corresponds to a shift of the points to the left side of the diagram).

circumstellar disk is spatially resolved and special coronographic technique of observations can be used to this purpose (Smith and Terrile, 1984; Paresce and Burrows, 1987; Gledhill *et al.*, 1991). In our case we deal with unresolved protoplanetary disks and we should wait for the stage when the star will be screened out by a dust cloud intersecting the line of sight.

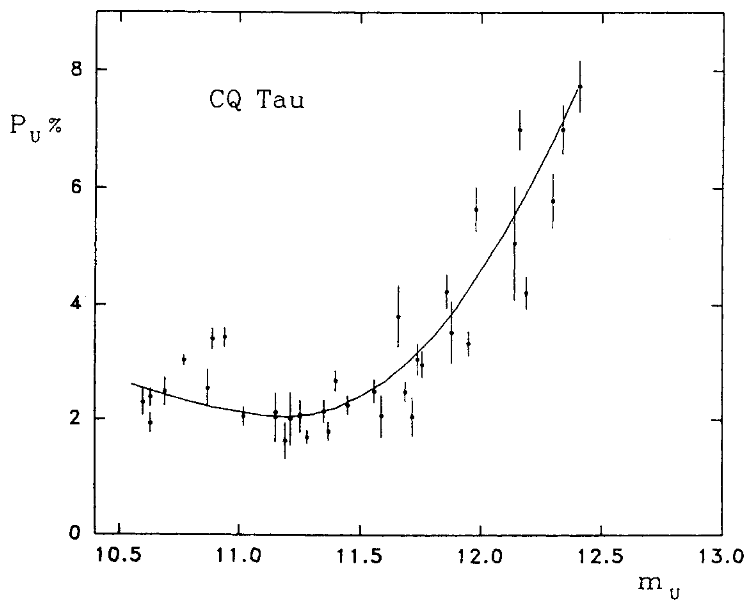
Let us note briefly some other results of our program related to the different questions of the physics of young stars.

Interpretation of color slopes on the color/magnitude diagrams is another important implication of our study. In the framework of the surface magnetic activity model, these slopes were interpreted as a result of temperature variations on the stellar surface (see, e.g., Vrba *et al.*, 1985). In the light of the above results, this interpretation should be revised: the reddening of the stars on the color-magnitude diagram actually reflects the variable circumstellar reddening and the slope of the color tracks depends on the absorption law in the circumstellar dust clouds. So, the initial (linear) part of the color tracks (Figures 1 and 10) is an important source of information about the optical properties of dust in young protoplanetary disks (Grinin, 1992).

Formation of intrinsic linear polarization of young stars. Some attempts of simultaneous photometric and polarimetric observations of young stars had been undertaken before our program (e.g., Efimov, 1980; Grinin *et al.*, 1980) but they all were fragmentary and their results are contradictory. The majority of polarimetric observations of Ae/Be Herbig stars were made without simultaneous photometry and their results are also contradictory (see Breger, 1974; Garrison and Anderson, 1978; Vrba *et al.*, 1979).



(a)



(b)

Figure 6 Two examples of the observed dependences of the linear polarization degree in the U band for WW Vul and CQ Tau from Grinin *et al.* (1991). The theoretical lines correspond to the best fit of the law (1) to the observations. In the case of CQ Tau the IS polarization is almost orthogonal to the intrinsic one (Berdjugin *et al.*, 1990), and in the bright state $P_{cs}(0) < P_{is}$. The competition between them in the minima gives the nonmonotonic depence of P_{obs} on the stellar magnitude.

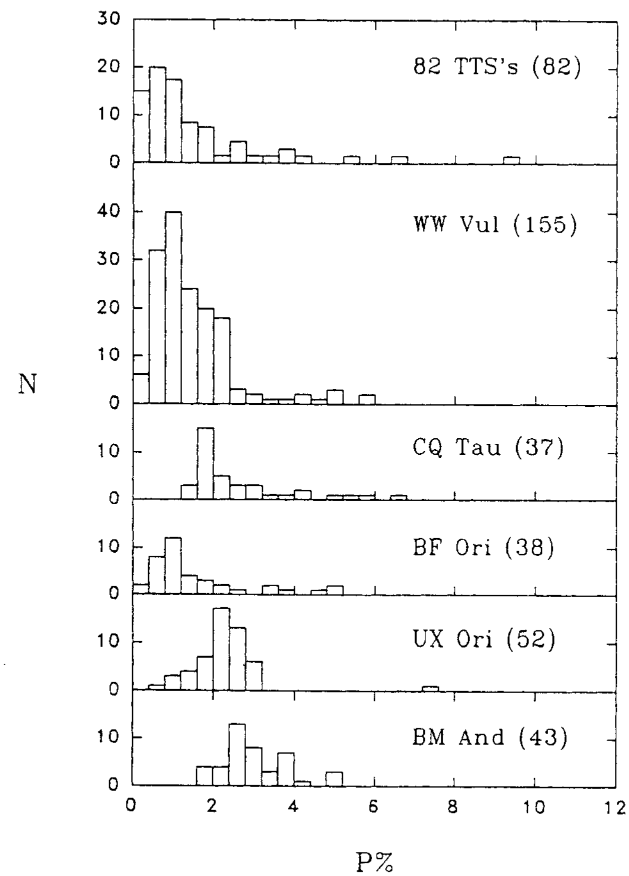


Figure 7 Top: the histogram of the observed linear polarization degree for a large group of T Tauri type stars from Bastien (1987). A typical value of P is about 1–2% and only a small group of TTSs has a high linear polarization ($P > 5\%$). Bottom: the histograms of the observed linear polarization for a few program stars. One bin corresponds to one observational night. One can see that in the bright state P does not differ from that of a typical TTS. However, sometimes each object goes over to the subclass of highly polarized young objects. These are just the moments of Algol-type minima.

Analyzing the state of the problem in 1984, Bastien (1985) notes the absence of any dependence between the polarization degree of young stars and their brightness. In his recent review (Bastien, 1988) he discusses two most probable sources of intrinsic linear polarization for young stars: the optical dichroism of circumteller dust and the scattering of stellar radiation in nonspherical dust envelope, and he is inclined to prefer the latter.

The contribution of our program into the solution of this problem contains: a) the discovery of a well-defined anticorrelation between the degree of linear polarization and the stellar brightness, b) the evidence that the main source of intrinsic linear polarization of young stars is the scattering of stellar radiation by circumstellar dust, and c) the main cause of its variability is a variable obscuration of the direct (unpolarized) radiation of a star by the CS dust clouds.

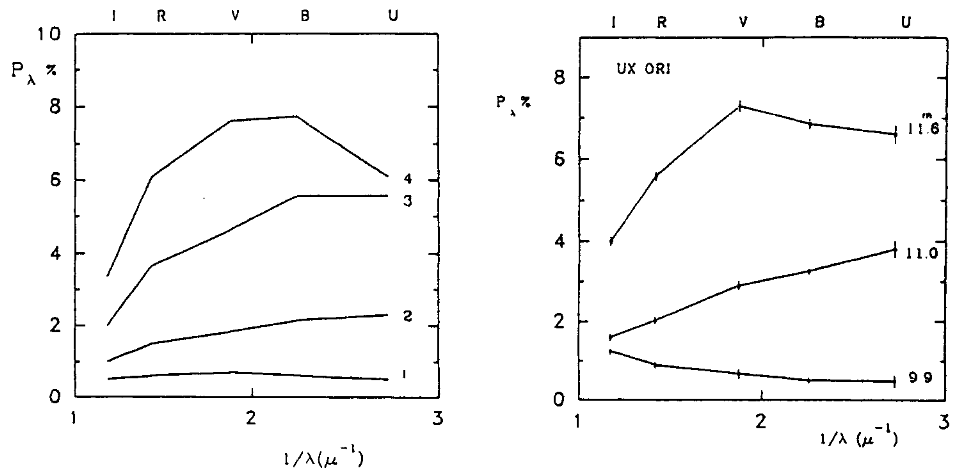


Figure 8 The observed wavelength dependence of the linear polarization of isolated Ae Herbig stars UX Ori at different brightness levels. The theoretical P_λ dependence for the case of best fit of polarimetric and photometric behavior of the star in deep minima are given to the left according to Voshchinnikov *et al.* (1988).

In this connection the question arises: what is the physical meaning of different dependences of the polarization degree and other parameters of young stars (see, e.g., Yudin, 1988) if: a) the linear polarization observations of these stars has been made without simultaneous photometry, and b) we know now that polarization degree of young stars can vary sometimes by an order of magnitude.

New approaches to the diagnostics of the circumstellar dust. The fact that we observe, in the deepest minima, the scattered radiation of the CS disks with a little contamination by direct stellar radiation permits us to obtain the most precise data on the intrinsic polarization of young stars and to use the new approaches for diagnostics of the CS matter (Voshchinnikov *et al.*, 1988; Voshchinnikov, 1989; Voshchinnikov and Grinin, 1991). In particular, using simultaneous multi-band observations of the linear polarization and stellar brightness we can estimate, using numerical simulations of Algol-type minima (Figures 8–10), such parameters of the CS dust which are difficult (or impossible) to estimate by other means as the optical properties of the grains, the size distribution, the envelope flatnesses, etc.

Let us note briefly some results obtained in this way:

1) From the numerical modeling (based on the Mie theory) of linear polarization of UX Ori (Voshchinnikov *et al.*, 1988) and WW Vul (Voshchinnikov and Grinin, 1991), it was found that the CS disks around these stars are strongly flattened: the aspect ratio A/B is about 3–4; the minimal size of the dust particles in the disks is $a_{\min} \simeq 0.04–0.05\,\mu$, that is an magnitude larger than in the IS medium. This means that the grain growth in young protoplanetary disks has already begun but the particles are not so large as in "old" CS disks like those around Vega type stars (Chini *et al.*, 1990) or β Pictoris (Paresce and Burrows, 1987; Telesko and Knacke, 1991).

2) In the case of WW Vul we estimated the sizes and masses of the dust clouds

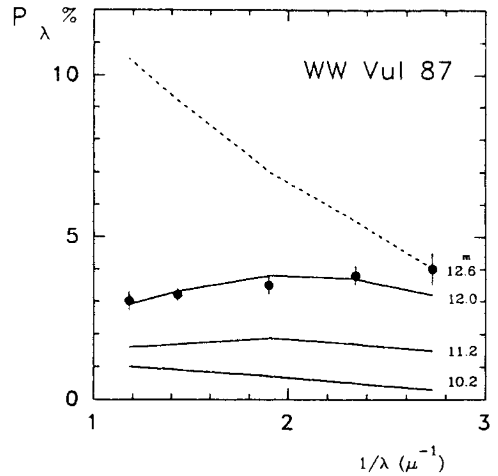


Figure 9. The theoretical P_λ wavelength dependence for the model of the minimum of WW Vul in 1987 (Voshchinnikov and Grinin, 1991). The points correspond to the observed P_λ dependence (corrected for the IS polarization) for the deepest part of the minimum. The dashed line corresponds to the case of full occultation of the star by the circumstellar dust cloud.

Note: One can see from this figure that the intrinsic polarization of WW Vul in the blue part of the spectrum (U band) was close to saturation in the deepest part of the minimum 1987. This means that we observed in this episode the scattered light of a protoplanetary disk with a little contamination by the direct stellar radiation.

intersecting the line of sight and producing the deep minima of 1987 and 1989. For example, the extremely deep minimum of 1987 has been caused by a dust cloud which intersected the line of sight at the distance from the star not larger than three astronomical units. The cloud has a central condensation of the size of about 0.15 A.U. embedded into a more extended envelope of the size $\simeq 0.7$ A.U. and the mass $M > 2 \times 10^{21}$ g.

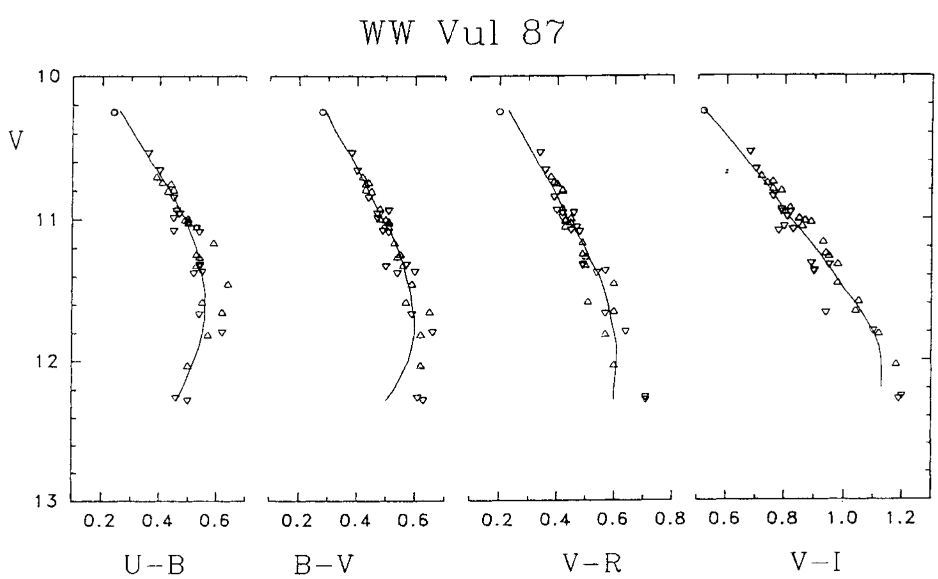


Figure 10 Fitting theoretical color-magnitude diagrams to the observations of WW Vul (Grinin *et al.*, 1988) in the minimum of 1987 (from Voshchinnikov and Grinin, 1991). The dust mixture is the same as in the interpretation of the wavelength dependences P_λ in Fig. 9.

It has also been shown (Voshchinnikov and Grinin, 1991) that the dust particles within the cloud and in the intercloud medium have about the same optical parameters. We concluded from this that, like the solar system (where the main source of interplanetary dust are the comets which loose the matter at the nearest approach to the Sun), in proto-planetary disks an intensive mass exchange between dust clouds and intercloud matter is realized in such a way.

The processes of this type may be important for understanding the question: how can the grains exist near a hot stars? For example, according to Tjin A Dje *et al.* (1984), the inner radius of the dust envelope around UX Ori is about 3 A.U. On the other hand, estimation shows that the dust should be swept away a long time ago by radiative pressure.

In the light of the above arguments we can assume that the dust is delivered to the neighborhood of a star at the near passing (and partial dissipation) of the dust clouds rotating around a star on elongated orbits.

Another important consequence of this process is the "contamination" of the stellar wind by heavy elements. The importance of such a "contamination" of the matter outflowing from young stars was demonstrated recently by Rawlings *et al.* (1988).

Orientation of circumstellar disks. Although the CS disks in our sample are not spatially resolved, we can find the orientation of their symmetry axes relative to the local magnetic field direction from the position angles of intrinsic polarization (in those cases when the latter can be found from IS polarization). Specifically, it was found that the axes of the CS disks around three investigated stars (WW Vul, BF Ori and BM And) are closely aligned with the local magnetic field (see Figures 11 and 12). Such an orientation means that magnetic field plays an important role at the initial phase of gravitational collapse of the protostellar cloud (see Mouschovias, 1976). As a result, the closest environment of a star (the

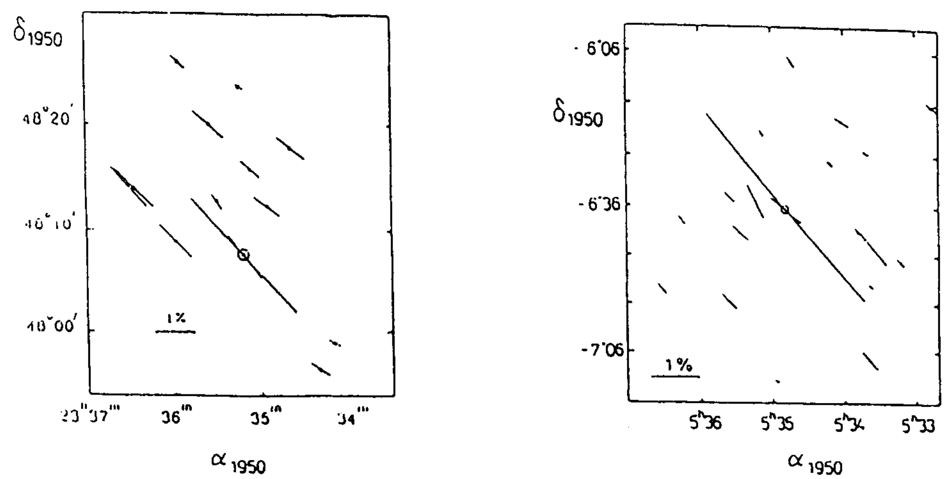


Figure 11. To the right: the IS polarization in the neighborhood of BF Ori, from Vrba *et al.* (1988), for the stars with $P < 1\%$ and the polarization of the star itself in the bright state and in the deep minima, from Grinin *et al.* (1989). To the left: the same for the T Tauri star BM And, from Grinin *et al.* (1991). In both cases the axes of protoplanetary disks are closely aligned with the local magnetic field.

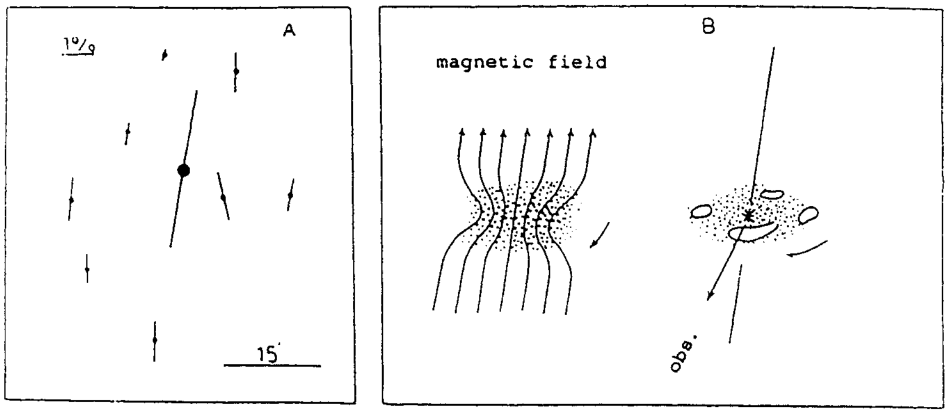


Figure 12 To the left: the same as in the Fig. 12 for WW Vul, from Grinin *et al.* (1988). To the right: a sketch of the gravitational collapse of a protostellar cloud in the magnetic field according to Mouschovias (1976).

protoplanetary disk in our case) preserves the memory of the direction of the magnetic field along which the initial collapse occurred (Figure 12)

The latter assertion is important in connection with the discussion of the mechanisms of alignment (along the IS magnetic field) of bipolar outflows from young stellar objects (Morgan *et al.*, 1984; Cohen *et al.*, 1984; Strom *et al.*, 1986). Two different mechanisms of such an alignment are possible (see, e.g., Cohen *et al.*, 1984): a direct channeling of the initially isotropic outflows in the IS magnetic field and the orientation of the CS disk (Königl, 1982) which can be also the source of the bipolar outflows (Heyvaerts and Norman, 1989). We have found the orientations of the CS disks themselves and our results support the latter interpretation.

It is clear that not only the CS disk but also the rotation axis of a star itself and the orbital plane of a double system can "remember" the direction of the magnetic field. Hence, one can expect the existence of stellar groups with aligned spins in our Galaxy. This possibility should be taken into account in the statistical studies of rotational velocities in young stellar clusters. It is useful to keep this in mind also when interpreting some strange properties in the distributions of the parameters of double system orbits (see Batten, 1973 and references therein).

R CrB stars. Let us note in conclusion an important "by-product" of our study related to the stars of quite another type, namely R CrB stars. These stars belong to a small group of chemically peculiar stars and are similar in some respects to those of our sample. From time to time, they fade, which is usually explained by the formation of graphite dust in their atmospheres (Alexander *et al.*, 1972). The intrinsic linear polarization of these stars increases in the minima and the color indices change in a complex way. In the deepest parts of the minima the "blueing" effect is observed, which is very similar to that encountered in our case. Beginning probably from the Pane-Gaposhkin (1962) paper and up to a recent time, the interpretation of this effect was connected also with the chromospheric emission. In favor of this (as in our case), the spectra of these stars testified: emission lines appeared in the deep minima.

This interpretation was recently revised by Pugach (1991) who has shown that the most natural explanation of the "blueing" effect in the minima of R Crb stars is connected, as in our case, with the scattered radiation of the circumstellar dust. The same correction has been made by Efimov (1991) for the origin of the linear polarization in these stars.

3. CONCLUSIONS

The intrinsic linear polarization of stars is one of the most delicate tools for the investigation of physical properties of the circumstellar matter. We demonstrated above how this tool can be used for better understanding of the variability mechanism of young stars. Another point which has just emerged, is the possibility of diagnostics of physical parameters of the CS dust around young stars.

Then an important question arises: does the β Pictoris phenomenon (an intensive comet-like activity) occur near the stars with young protoplanetary disk? To answer this question, spectral observations of these stars with high spectral resolution and S/N ratio are required, especially in the deep minima.

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