universe

Review

Scattered Radiation of Protoplanetary Disks

Vladimir P. Grinin [1,2,*] and Larisa V. Tambovtseva [1]

1 Pulkovo Observatory of the Russian Academy of Sciences, 196140 Saint Petersburg, Russia; lvtamb@mail.ru
2 V.V. Sobolev Astronomical Institute, Saint Petersburg State University, 198504 Saint Petersburg, Russia
* Correspondence: grinin@gao.spb.ru

Abstract: Scattered radiation of circumstellar (CS) dust plays an important role in the physics of young stars. Its observational manifestations are various but more often they are connected with the appearance of intrinsic polarization in young stars and their CS disks. In our brief review we consider two classes of astrophysical objects in which the participation of scattered radiation is key for understanding their nature. First of all, these are irregular variables (UX Ori type stars). The modern idea of their nature and the mechanism of their variability has been formed thanks to synchronous observations of their linear polarization and brightness. The second class of objects is the CS disks themselves. Their detailed investigation became possible due to observations in polarized light using a coronographic technique and large telescopes.

Keywords: protoplanetary disk; scattered radiation; linear polarization; UX Ori stars; RW Aur

check for updates

Citation: Grinin, V.P.; Tambovtseva, L.V. Scattered Radiation of Protoplanetary Disks. *Universe* **2022**, *8*, 224. https://doi.org/10.3390/universe8040224

Academic Editors: Galina L. Klimchitskaya, Vladimir M. Mostepanenko and Nazar R. Ikhsanov

Received: 14 February 2022
Accepted: 30 March 2022
Published: 2 April 2022

1. Introduction

Scattered radiation of circumstellar disks, as a rule, makes a small contribution to the optical radiation of young stars. The exception is a subclass of irregular variable stars with UX Ori as a prototype [1], and a small number of highly embedded stars and stars with edge-on disks. The family of UX Ori stars includes mainly the stars of the Ae spectral type. For a long time broadband photometric observations were the only method for their investigation. However, such observations could not unambiguously determine the mechanism of their unusual variability, representing a sequence of stochastic brightness weakening with an amplitude up to 2–3^m and duration from a few days to a few weeks. The same observations can often be explained in completely different ways. For example, the reddening of the star with a decrease in its brightness has been equally well interpreted with both an increase in the CS extinction [2], and an appearance of magnetic spots on the star [3].

The important role of scattered radiation in understanding the nature of the variability of these objects was first pointed out by one of the authors of this paper [4]. During the deep brightness minima caused by screening the star with the CS gas and dust clouds, the direct radiation of the star is blocked by the screen. At such moments, the scattered radiation of the CS dust dominates the observed radiation. This explains a range of properties of these objects, including the unusual behavior of color indices at brightness fading, restriction of the brightness amplitudes and increases in the linear polarization in the brightness minima. Based on these facts, Grinin et al. [5] determined the evolutionary status of the stars from this subclass: the UX Ori stars (or UXOrs) are usually young stars, namely, intermediate-mass Herbig Ae stars surrounded by protoplanetary disks, and they differ from the usual photometrically inactive Herbig stars only with a small inclination of their CS disks to the line of sight. This conclusion has been supported by further investigations [6,7], including interferometric observations in the near-infrared region of the spectrum [8,9].

It should be noted that an addition of the photometrically active UX Ori type stars to the photometrically inactive ("classical") Herbig AeBe stars had a strong influence on the further development of our ideas about all classes of Herbig stars. It turned out that these stars are not surrounded by spherical gas and dust envelopes, as previously assumed (see, e.g., [10]), but by circumstellar disks. It was also found that the Herbig stars demonstrate not only spectral signs of the matter outflow but also signs of accretion. It all depends on the angle between the disk plane and the line of sight [11,12].

2. Coronographic Effect

During the long-standing photopolarimetric observations of the UX Ori type stars, it turned out that the observed changing in the linear polarization parameters is well described with the model suggested in [4]. It claims that the CS dust clouds obscure the star from the observer but do not influence the optical properties of the scattered radiation of the CS disk. The latter means that the shadow zones on the disk created by the clouds are much smaller in comparison with its size. Herewith the dust cloud themselves also do not influence the polarization of the stellar radiation that passes through them. The latter means that the dust grains in the clouds are not lined up. In this condition, changes in the intensity of the observed radiation during the eclipse I_{obs} are described with the following simple relationship:

$$I_{obs} = I_* e^{-\tau_\lambda} + I_{sc}, \tag{1}$$

where I_* is the intensity of the stellar radiation out of the eclipse, τ_λ is the optical depth of the cloud screening the star at the wavelength λ, and I_{sc} is the intensity of the scattered radiation, which is considered unchanged during the eclipse, as was mentioned above.

The dependence of τ on λ is assumed as $\tau_\lambda = \tau f(\lambda)$, which suggests that within the stellar disk the screen is homogeneous (this permits us to treat the star as a point source of light), and dependence of its optical depth on the wavelength does not change during the eclipse. The latter assumption is based on a very important observational fact: the existence of the straight section on the color–magnitude diagram that is used to determine the CS extinction law (see, e.g., [13]).

From Formula (1) one can directly obtain a link between the intensity of the scattered radiation of the disk and the possible maximum amplitude of the stellar brightness reduction:

$$(\Delta m)_{max} = 2.5 \log(1 + I_*/I_{sc}), \tag{2}$$

Knowing the magnitudes $(\Delta m)_{max}$ from the photometric observations, one can immediately find for each star the contribution of the scattered radiation of the CS disk to the optical radiation of the star out of the eclipse. On average about 10% [4] is confirmed when modeling the interferometric observations [9].

This model explains changes in the color indices observed in UX Ori type stars during the brightness minima (Figure 1), and describes well the observational link between the brightness variations and parameters of the linear polarization of these stars. It permits us to distinguish with high accuracy between the intrinsic polarization of the star caused by the scattered radiation of the CS disk and the interstellar one:

$$\mathbf{P}_{obs} = \mathbf{P}_{IS} + \mathbf{P}_{in}(\Delta m), \tag{3}$$

Here $\mathbf{P}_{obs}$, $\mathbf{P}_{IS}$ and $\mathbf{P}_{in}$ are pseudo-vectors of the observed, interstellar and intrinsic polarization of the investigated star, and Δm is the amplitude of the diminution of the star brightness counted from its brightest state.

$$\mathbf{P}_{in}(\Delta m) = \mathbf{P}_{in}(0)\, e^{-0.4\,\Delta m}. \tag{4}$$

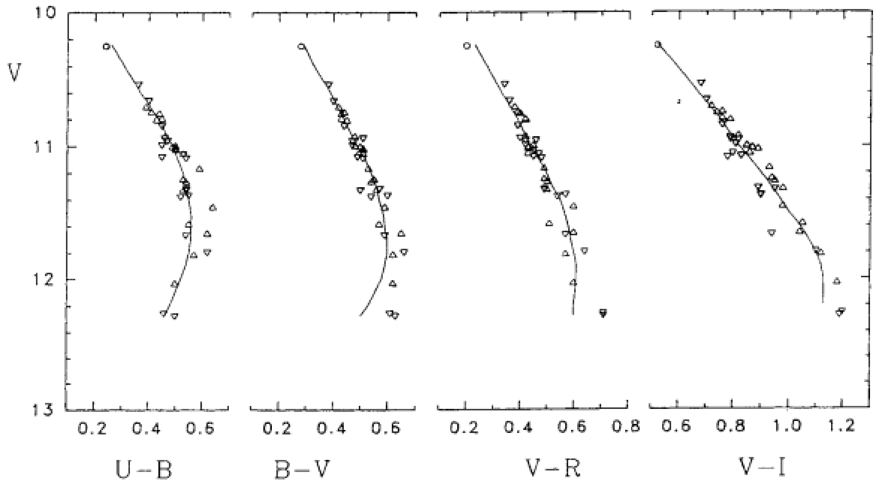

Figure 1. Color–magnitude diagram of the UX Ori type star WW Vul from observations of the deep brightness minimum in 1997 [14]. Open circles mark the ascending part of the minimum; triangles mark its descending part. Lines show theoretical dependencies calculated in [15] on the base of Equation (1).

After making up such equations for each *i*-th observation, we obtain a redundant system of equations for each photometric band. The solution of such a system with the least square method allows us to find two unknown quantities, $\mathbf{P}_{IS}$ and $\mathbf{P}_{in}(0)$. Each of them is a pseudo-vector that gives the degree of the interstellar and intrinsic polarization and their position angles. Thus, for each photometric band the model solution is obtained on the base of the observed photometry and polarimetry of the object investigated. Then, this information is used for modeling the physical parameters of the CS dust (including the chemical composition and the particle size distribution), and what is more important, parameters of the protoplanetary disks (see, e.g., [16–18]). The most important results obtained in this field are as follows: (1) the circumstellar dust in the surface layers of the protoplanetary disks is close to the dust in the interstellar medium with its chemical composition and differs from it in minimum grain size, which is about an order of magnitude larger than that in the interstellar medium; and (2) the best agreement with observations is provided by the model of the protoplanetary disk with thickening in the dust evaporation zone [18]. In particular, this model explains a non-trivial observational fact: the hopping change in the position angle of the linear polarization in some young stars with changing in the wavelength of the radiation [19].

As an example, in Figure 2 it is shown that the linear polarization degrees depend on the brightness of the UX Ori type star WW Vul in the *U* band from [14]. One can see that it corresponds rather well with the model curve calculated on the base of Equations (2) and (3). Generally, the results of the synchronous observations of the linear polarization and the brightness of the UX Ori type stars show that, like in T Tauri stars [20], the main source of the linear polarization in the Herbig Ae stars in the visible spectrum is the scattered radiation of the circumstellar dust. The role of the optical dichroism in the formation of intrinsic polarization in the young stars is negligible. The circumstellar clouds intersecting the line of sight play the role of a natural coronograph: in blocking the direct radiation of the star, they permit us to observe the weak scattered radiation of the disk. This radiation turned out highly polarized (5–8%) [5], leading to the conclusion about the small inclinations of the disks in UX Ori type stars to the line of sight.

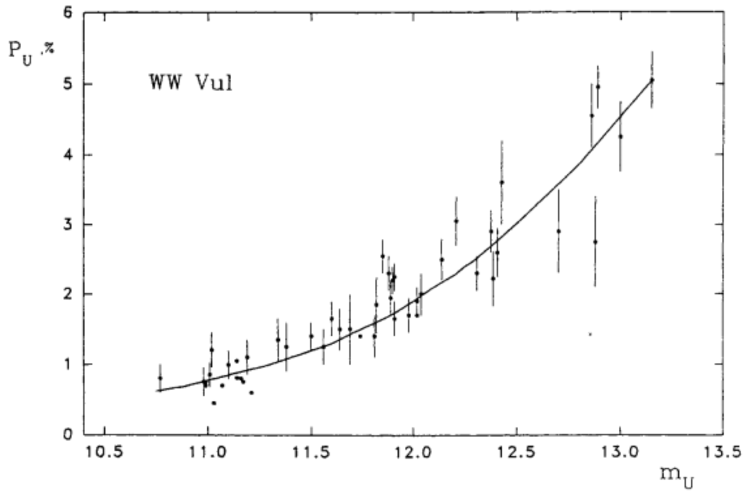

Figure 2. Dependence of the linear polarization degree on the brightness of the UX Ori type star WW Vul in the *U* band from [14]. Lines show theoretical dependencies calculated using Equations (2) and (3).

2.1. Simulations of Long-Lasting Eclipses

Cases are known in which eclipses of the UX Ori type stars lasted several months. During such events an interesting phenomenon was observed: the change in the position angle of polarization was out of sync with the change in the star brightness [14,21]. Simulation of such events showed [22] that the reason of these anomalies was an obscuration of a noticeable part of the disk with the dust screen. This led to the appearance of vast shadows on the disk whose movement on the disk behind the screen generated changes in the parameters of the disk intrinsic polarization. Of course, in such cases the coronographic effect mentioned above cannot be realized completely.

Very seldom are deep eclipses lasting more than a year observed in young stars [23–27]. Their physics apparently differs from the simple model of the CS dust cloud transit across the stellar disk accepted for the UX Ori type stars. Such eclipses indicate the appearance of a large amount of matter in the nearest vicinity of the star, for example, as a result of the fall of massive gas and dust blobs from the remnant of the protostellar cloud onto the CS disk. Such a type of cloudy accretion onto the young objects was discussed in the literature according to FUORs outbursts [28]. Certain hopes were placed on this mechanism in connection with the discussion of the nature of the eclipses of UX Ori type stars [29]. However, this hypothesis did not receive support because of the significantly modest scale of the eclipses observed in these stars. This can be due to density fluctuations in the dusty atmosphere of the disk, or in the disk wind.

In the case of eclipses lasting years, the cloudy accretion may well be a source of matter into which the young object is temporarily immersed. In favor of this suggestion two observational facts testify: (1) an increase in infrared fluxes at the wavelengths ≥ 2 µm observed during the optical minima in some T Tauri stars [30–32] (this means that during such events the CS dust blocks the large amount of stellar radiation and that this dust is fairly close to the star); (2) an increase in the linear polarization of one of them (RW Aur) up to 30% in the *I* band [33]. Such high polarization is typical for very young stars immersed in gas and dust cocoons. Its source is the radiation of the star scattered in the polar (optically semi-transparent) regions of the cocoon [34]. The position angle (P.A.) of linear polarization in such objects is parallel to the disk plane (see, e.g., [33]).

2.2. Scattering by Moving Dust

As is known, the main part of the thermal radiation of the protoplanetary disks in the near-infrared spectrum region originates near their inner boundary of the dust sublimation zone [35,36]. In the vicinity of this region, the main part of the scattered radiation is also formed. In T Tauri stars this region is at a distance of 5–10 stellar radii and rotates with velocities of about 150–200 km/s. Therefore, in the scattering of stellar radiation by dust particles the frequency of the scattered radiation will change due to the Doppler effect [37,38]. For the broadband observations this effect has no meaning. However, when studying the spectra of the UX Ori type stars and relative objects it has to be taken into account. Such a problem was first solved in [39]. An example of the photospheric line transformation in the spectrum of the T Tauri type star during the deep brightness minimum is presented in Figure 3. It is seen that at first in the absorption line wide wings appear due to an increase in the contribution of the scattered radiation. In the deep minimum the photospheric line transforms into a shallow but wide absorption band. Keeping in mind that the spectrum of T Tauri type star is rich with photospheric lines, one should expect that in its spectrum of the scattered radiation wide bands will overlap because of blending and form a quasi-continuum [40]. This case is illustrated by the fragment of the synthetic spectrum of the typical T Tauri star in the vicinity of Ca I 6103 and 6122 Ålines shown in Figure 4 in the bright state and in the deep minimum. Namely, the same spectrum transformation was recently observed at the deep brightness minimum for RW Aur [41,42].

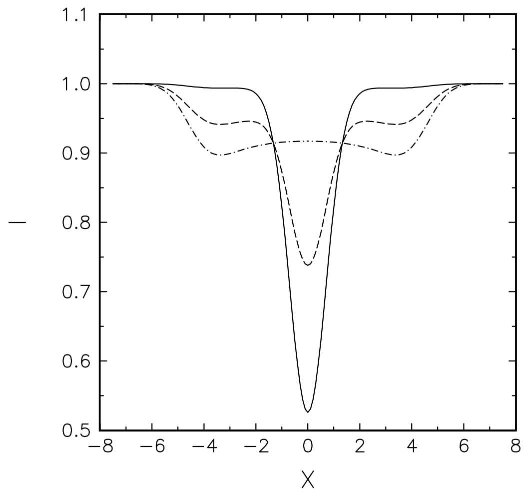

Figure 3. Photospheric line broadening in the T Tauri type star (solid line) during an eclipse due to scattering at the inner boundary of the protoplanetary disk. The dot-dashed line corresponds to the total eclipse.

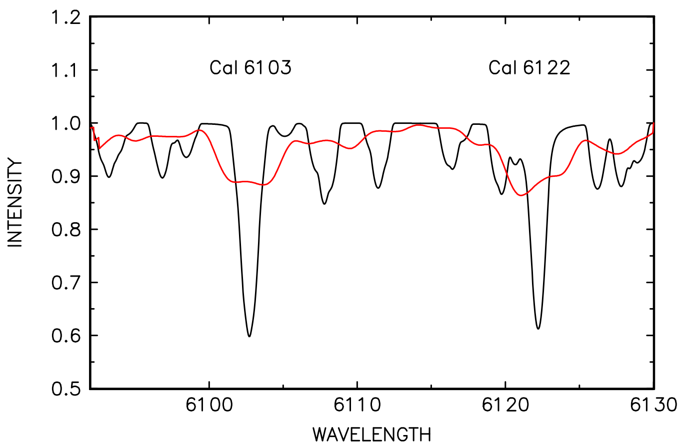

Figure 4. A part of the synthetic spectrum of RW Aur in the vicinity of the Ca I 6103 and 6122 Å lines in the bright state (black) and the deep minimum (red).

The other source of the intrinsic polarization of young stars can be the dust component of the disk wind [18]. In this case the moving dust has two velocity components: tangential and poloidal ones. Therefore, the scattering of stellar radiation by the disk wind can lead to more complex transformation of the photospheric lines: to the line broadening due to rotation and redshift due to the poloidal motion. This issue is briefly discussed in [38,39] and deserves a more detailed quantitative analysis.

In UX Ori type stars the effect considered above is revealed in a significantly weaker form [38]. This is caused by two reasons: (1) in most of these stars the photospheric lines are broadened by the strong stellar rotation; (2) the dust sublimation zone is located much farther from the star due to the higher luminosity. Therefore, the Keplerian velocities of the disk in this region are significantly less compared to those in T Tauri stars. Figure 5 demonstrates the part of the synthetic spectrum of the UX Ori type star CQ Tau in the vicinity of the Fe II 5018 line in the bright state and the deep minimum. It is seen that in this case the spectrum of the scattered radiation differs little from the photospheric one.

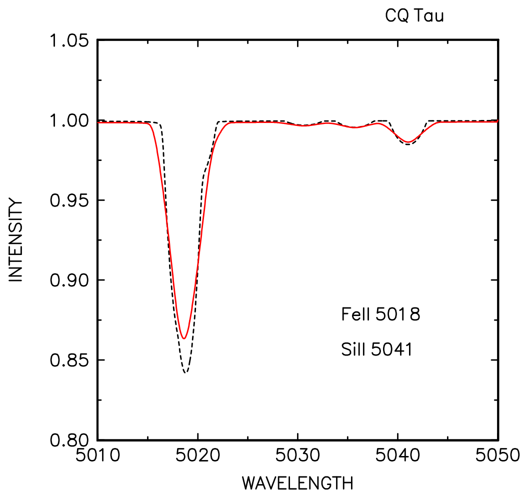

Figure 5. A part of the synthetic spectrum of CQ Tau in the vicinity of the Fe II 5018 Å line in the bright state (black) and the deep minimum (red).

The same occurs in the emission lines in the spectra of young stars. Nevertheless, the influence of the scattered radiation on the emission lines is well known from the observations of the linear polarization (see [43] and cited papers therein). When traversing the Hα line profile, both the value and position angle change, which reflects the contribution of various parts of the CS disk to the polarization of the different parts of the line profile. As shown in [43], this effect is sensitive to the parameters of the inner CS disk regions, and may shed additional light on their structure.

3. Images of Circumstellar Disks in the Scattered Light

The coronographic method has been very successful in observations of the scattered radiation of the CS debris disks. In particular, with its help Smith and Terrile [44] first observed the circumstellar disk of β Pictoris. This disk is seen nearly edge-on on the coronographic image. Therefore, its radiation (as well as the radiation of the UX Ori type stars) was found to be strongly polarized [45]. The coronographic observations with HST revealed that the inner region of the β Pic disk was slightly curved relative to its outer part [46]. The authors of the paper quoted above suggested that this curvature was caused by a disturbing body (a massive planet) whose orbit was slightly inclined relative to the plain of the outer disk. Fourteen years later this planet has been found [47], also with the coronagraphic technique. An important contribution to such observations has been made with the Hubble Space Telescope (see, e.g., [48,49] and references there).

At the present time the technique of observations of weak objects in the vicinity of stars based on the coronographic method is widely used in the different astrophysical fields, among them the study of the fine structure of the circumstellar disks in polarized light (see, e.g., [50–53] and the references therein). Of particular interest are the first and rather successful attempts to monitor the protoplanetary disk images in the polarized light [51]. They showed that on the images of the CS disk of HD 135344B (observed nearly pole-on), the shadows were caused by absorption of the stellar radiation by local perturbations in the inner disk. These shadows are manifested as narrow radial bands of the variable brightness, and also as the wide bands caused by absorption by large scale structures. These observations point to the direct physical connection between eclipses of the UX Ori type stars and shadow formation on the circumstellar disks.

Another example of successful monitoring of a circumstellar disk in the polarized light is the long-term observations of CQ Tau [54]. This star is one of the most active members of the UXOrs family [55], having a very complex light curve [56]. According to interferometric observations in the near-IR [57] and millimeter wavelengths [58,59], the inner and outer parts of the CS disk of CQ Tau have different inclinations: $i = 48.5 \pm 5^\circ$ and $i = 35^\circ$, correspondingly. In such cases, a narrow shadow from the inner disk can be observed on the outer one (see, e.g., [60–62]). The observations of CQ Tau have demonstrated that such a shadow exists on the peripheral region of its CS disk [54].

The aforementioned interferometric observations of CQ Tau support the point of view according to which the extinction events in UX Ori stars take place in the innermost part of the CS disk where the NIR radiation is formed. Continuation of such observations is of undeniable interest for understanding the nature of the perturbations in the inner regions of CS disks, which can be caused by different reasons such as an azimuthal heterogeneity of the dusty disk wind, collisions of planetesimals or hydrodynamical fluctuations in the dust evaporation zone of the disk.

If the extinction events are driven by the disk wind, the UXOrs activity will depend not only on the disk inclination but also on the mass loss rate and the dusty wind loading area. The latter depends on the magnetic field in the disk and the star luminosity. The mass loss and accretion rates are closely connected. Therefore, in this case the UXOrs activity will be sensitive to the disk inclination, as well as the stellar luminosity and mass accretion rate.

The Edge-On Disks

Young stars with edge-on CS disks are also observed through scattered light. The prototype of such objects is the well-known T Tauri star HH 30. The first image of this object was obtained with high resolution by Burrows et al. [46] with the Hubble Space Telescope. It revealed a flared CS disk (in accordance with the prediction of the Shakura and Sunyaev [63] model (see Kenyon and Hartmann [64]) and the highly asymmetric jet. In addition to the jet, a conical molecular outflow is also observed in the CO lines [65]. Photometric and polarimetric observations have shown that HH 30 is a variable object [66–68]. It demonstrates the periodic variability of brightness and linear polarization with a period of 7.49 days [67]. The physical model of such a periodicity is not clear. It could be a hot spot on the rotating star or periodic variations of the CS extinction in the star's vicinity.

Variable illumination of the disk leads to changes in its shape [67]. These changes are one of the most interesting manifestations of the circumstellar activity of young stars reminiscent of the moving shadows on the disk images [50]. The other non-trivial special property of HH 30 is its almost one-side jet and molecular outflow [46,64,69]. The origin of such asymmetric outflows is discussed in [70]. An opposite case of the edge-on disk with a well-developed and almost symmetrical jet is HH 212 [71].

To date, more than ten young stars with edge-on disks are known (see, e.g., [72] and the references there). Most of them are T Tauri stars. Observations and modeling of such objects permit us to study in detail the internal structure of CS disks (see, e.g., [73,74]). It is obvious that the spectra of such objects are strongly distorted by the scattered radiation [37].

4. Intrinsic Polarization of Young Stars and Orientation of Their CS Disks

The position angle of linear polarization depends on the geometry of the scattering medium. Calculations show [75] that in models with the classical accretion disk (with a flared surface) the P.A. is orthogonal to the disk plane. In the stars at earlier evolutionary stages surrounded by accreting envelopes the P.A. is parallel to the disk plane [76]. The average age of the UX Ori type stars is several million years [77]. Therefore, most of them belong to the first group of young stars. Keeping in mind what was mentioned above, one can use the position angle of the intrinsic polarization in order to determine the orientation of protoplanetary disks in the projection on the sky plane. Such a possibility was confirmed by results of interferometric observations of UX Ori in the near-infrared spectrum region: according to [9] the position angle of the symmetry axis of its circumstellar disk is equal to $127.5 \pm 24.5^{\circ}$. Polarimetric observations of UX Ori in the deep minima give P.A. = 125°–129° [21,78]. Orientation of the circumstellar disk of another UX Ori type star VV Ser is determined with the position of the shadow formed by the disk on the reflective nebula behind the star. According to [79], the P.A. of the shadow is equal to $15 \pm 5^{\circ}$, which corresponds to the P.A. of the disk symmetry axis $105 \pm 5^{\circ}$. Observations of the intrinsic polarization of VV Ser gives the position angle in the close range: P.A. = 88°–100° [80].

These two examples testify that the linear polarization of most UX Ori type stars in the deep brightness minima in fact characterizes the position of the symmetry axis of the circumstellar disk on the sky plane, and this position can be compared with the direction of the interstellar magnetic field determined with the help of polarization of the neighboring stars. Unfortunately, this is not always possible because of the complex structure of the interstellar magnetic fields in star formation regions. Figure 6 shows an example of the polarization map of the BM And, as well as the vicinity in which the polarization pseudo-vectors of BM And itself are shown in the bright stage and deep brightness minimum. It is seen that the interstellar magnetic field in the stellar vicinity is fairly homogeneous in direction, and the position angle of the stellar intrinsic polarization coincides with this direction with high accuracy [81]. This implies that the interstellar magnetic filed controlled the star formation process from the protostellar cloud, and that the circumstellar disk of the star "remembered" the direction of the magnetic lines.

Similar results have also been obtained during photopolarimetric observations for three other UX Ori type stars: WW Vul [14], BF Ori [82] and VV Ser [79,83,84]. Furthermore, the same method was used in [85] for a large group of Herbig AeBe stars. It was shown that subsamples of the more polarized stars from their list present a statistically significant tendency toward intrinsic polarization aligned with the interstellar magnetic field.

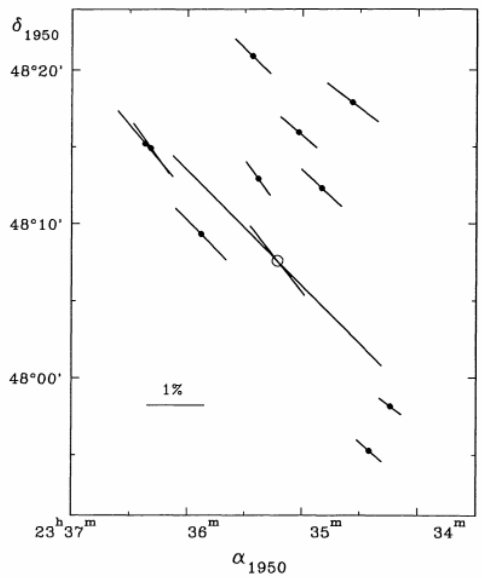

Figure 6. Polarization map of the BM and as well as the neighborhood from [81,84]. Two values of the star polarization are given: at the bright state and at the deep minimum. Credit: Grinin et al. 1995, A&AS, 112, 457, reproduced with permission © ESO.

5. Conclusions

Thus, although the scattered radiation of protoplanetary disks makes up only a very small part of the radiation of young stars, its existence provides us very important information about young stars and their circumstellar environment. Of great interest is the possibility to study the orientation of CS disks not resolved in a telescope with the help of polarimetric observations. Polarized radiation makes it possible to see fine details on the disk images and study their structure and variability. Photopolarimetric observations of UXOrs and their modeling permit us to investigate the perturbations in the innermost regions of the disks where planetary systems are formed.

Author Contributions: V.P.G.—conceptualization, data analysis and writing-editing; L.V.T.—numerical modelling and writing—editing; All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the financial support of the Ministry of Science and Higher Education of the Russian Federation (grant no. 075-15-2020-780).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All necessary data are contained in this paper.

Acknowledgments: The authors are grateful to the reviewers for useful comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Herbst, W.; Herbst, D.K.; Grossman, E.J.; Weinstein, D. Catalogue of UBVRI Photometry of T Tauri Stars and Analysis of the Causes of Their Variability. *Astrophys. J.* **1994**, *108*, 1906–1923. [CrossRef]
2. Wenzel, W. Extremely young stars. In *Non-Periodic Phenomena in Variable Stars*; Detre, L., Eds.; Academic Press: Budapest, Hungary, 1969; pp. 61–73.
3. Herbst, W. T Tauri Variables. *Publ. Astron. Soc. Pac.* **1986**, *98*, 1088–1094. [CrossRef]
4. Grinin, V.P. On the Blue Emission Visible during Deep Minima of Young Irregular Variables. *Sov. Astron. Lett.* **1988**, *14*, 27–28.
5. Grinin, V.P.; Kiselev, N.N.; Minikulov, N.K.; Chernova, G.P.; Voshchinnikov, N.V. The investigations of 'zodiacal light' of isolated Ae-Herbig stars with non-periodic Algol-type minima. *Astrophys. Space Sci.* **1991**, *186*, 283–298 [CrossRef]
6. Natta, A.; Grinin, V.P.; Mannings, V.; Ungerechts, H. The Evolutionary Status of UX Orionis-Type Stars. *Astrophys. J.* **1997**, *491*, 885–890. [CrossRef]
7. Pontoppidan, K.M.; Dullemond, C.P.; Blake, G.A.; Boogert, A.C.A.; van Dishoeck, E.F.; Evans, N.J., II; Kessler-Silacci, J.; Lahuis, F. Modeling Spitzer Observations of VV Ser. I. The Circumstellar Disk of a UX Orionis Star. *Astrophys. J.* **2007**, *656*, 980–990 [CrossRef]
8. Kreplin, A.; Weigelt, G.; Kraus, S.; Grinin, V.; Hofmann, K.-H.; Kishimoto, M.; Schertl, D.; Tambovtseva, L.; Clausse, J.-M.; Massi, F.; et al. Revealing the inclined circumstellar disk in the UX Ori system KK Ophiuchi. *Astron. Astrophys.* **2013**, *551*, A21–A27. [CrossRef]
9. Kreplin, A.; Madlener, D.; Chen, L.; Weigelt, G.; Kraus, S.; Grinin, V.; Tambovtseva, L.; Kishimoto, M. Resolving the inner disk of UX Orionis. *Astron. Astrophys.* **2016**, *590*, A96–A101. [CrossRef]
10. Miroshnichenko, A.; Ivezic, Z.; Elitzur, M. On Protostellar Disks in Herbig Ae/Be Stars. *Astrophys. J.* **1997**, *475*, L41–L44. [CrossRef]
11. Grinin, V.P.; Rostopchina, A.N. Orientation of circumstellar disks and the statistics of H_α profiles of Ae/Be Herbig stars. *Astron. Rep.* **1996**, *40*, 171–178.
12. Vioque, M.; Oudmaijer, R.D.; Baines, D.; Mendigutia, I.; Perez-Martinez, R. Gaia DR2 study of Herbig Ae/Be stars. *Astron. Astrophys.* **2018**, *620*, A128–A145. [CrossRef]
13. Pugach, A.F. Optical Properties of the Circumstellar Dust around Stars with Aperiodic Fadings. *Astron. Rep.* **2004**, *48*, 470–475. [CrossRef]
14. Grinin, V.P.; Kiselev, N.N.; Minikulov, N.K.; Chernova, G.P. Linear Polarization in Deep Minima of WW-Vulpeculae. *Sov. Astron. Lett.* **1988**, *14*, 219–223.
15. Voshchinnikov, N.V.; Grinin, V.P. Dust around Young Stars—Model of Envelope of the Ae Herbig Star WW-Vulpeculae. *Astrophysics* **1991**, *34*, 84–95. [CrossRef]
16. Voshchinnikov, N.V.; Grinin, V.P.; Karyukin, V.V. Monte Carlo simulation of light scattering in the envelopes of young stars. *Astron. Astrophys.* **1995**, *294*, 547–554.

17. Natta, A.; Whitney, B.A. Models of scattered light in UXORs. *Astron. Astrophys.* **2000**, *364*, 633–640.
18. Shulman, S.G.; Grinin, V.P. Influence of the Disk Wind on the Intrinsic Polarization of Young Stars. *Astron. Lett.* **2019**, *45*, 384–395. [CrossRef]
19. Pereyra, A.; Girart, J.M.; Magalhaes, A.M.; Rodrigues, C.V.; de Araujo, F.X. Near infrared polarimetry of a sample of YSOs. *Astron. Astrophys.* **2009**, *501*, 595–607. [CrossRef]
20. Bastien, P.; Landstreet, J.D. Polarization observations of the T Tauri stars RY Tauri, T Tauri, and V866 Scorpii. *Astrophys. J.* **1979**, *229*, L137–L140. [CrossRef]
21. Grinin, V.P.; The, P.S.; de Winter, D.; Giampapa, M.; Rostopchina, A.N.; Tambovtseva, L.V.; van den Ancker, M.E. The β Pictoris phenomenon among young stars. I. The case of the Herbig Ae star UX Orionis. *Astron. Astrophys.* **1994**, *292*, 165–174.
22. Shulman, S.G.; Grinin, V.P. Influence of Large-Scale Perturbations in Circumstellar Disks on the Linear Polarization Parameters of UX Ori Stars. *Astron. Lett.* **2019**, *45*, 664–676. [CrossRef]
23. Bouvier, J.; Grankin, K.; Ellerbroek, L.E.; Bouy, H.; Barrado, D. AA Tauri's sudden and long-lasting deepening: Enhanced extinction by its circumstellar disk. *Astron. Astrophys.* **2013**, *557*, A77–A86. [CrossRef]
24. Rodriguez, J.E.; Pepper, J.; Stassun, K.G.; Siverd, R.J.; Cargile, P.; Beatty, T.G.; Gaudi, B.S. Occultation of the T Tauri Star RW Aurigae A by its Tidally Disrupted Disk. *Astrophys. J.* **2013**, *146*, 112–122. [CrossRef]
25. Semkov, E.H.; Peneva, S.P.; Ibryamov, S.I. The pre-main-sequence star V1184 Tauri (CB 34V) at the end of prolonged eclipse. *Astron. Astrophys.* **2015**, *582*, A113–A119. [CrossRef]
26. Grinin, V.P.; Barsunova, O.Y.; Sergeev, S.G.; Shugarov, S.Y.; Fedorova, E.I. Unusual Eclipse of the UX Ori Type Star V719 Per. *Astron. Rep.* **2021**, *65*, 864–868. [CrossRef]
27. Bozhinova, I.; Scholz, A.; Costigan, G.; Lux, O.; Davis, C.J.; Ray, T.; Boardman, N.F.; Hay, K.L.; Hewlett, T.; Hodosan, G.; et al. The disappearing act: A dusty wind eclipsing RW Aur. *Mon. Not. R. Astron. Soc.* **2016**, *463*, 4459–4468. [CrossRef]
28. Hartmann, L.; Kenyon, S.J. The FU Orionis Phenomenon. *Annu. Rev. Astron. Astrophys.* **1996**, *34*, 207–240. [CrossRef]
29. Graham, J.A. Clumpy Accretion onto Pre-Main Sequence Stars. *Publ. Astron. Soc. Pac.* **1992**, *104*, 479–488. [CrossRef]
30. Grinin, V.P.; Arkharov, A.A.; Barsunova, O.Y.; Sergeev, S.G.; Tambovtseva, L.V. Photometric activity of the UX Ori star V1184 Tau in the optical and near-infrared spectral ranges. *Astron. Lett.* **2009**, *35*, 114–120. [CrossRef]
31. Shenavrin, V.I.; Petrov, P.P.; Grankin, K.N. Hot Dust Revealed during the Dimming of the T Tauri Star RW Aur A. *Inf. Bull. Var. Stars*. **2015**, *6143*, 1.
32. Covey, K.R.; Larson, K.A.; Herczeg, G.J.; Manara, C.F. A Differential Measurement of Circumstellar Extinction for AA Tau's 2011 Dimming Event. *Astrophys. J.* **2021**, *161*, 61–77. [CrossRef]
33. Dodin, A.; Grankin, K.; Lamzin, S.; Nadjip, A.; Safonov, B.; Shakhovskoi, D.; Shenavrin, V.; Tatarnikov, A.; Vozyakova, O. Analysis of colour and polarimetric variability of RW Aur A in 2010–2018. *Mon. Not. R. Astron. Soc.* **2019**, *482*, 5524–5541. [CrossRef]
34. Elsasser, H.; Staude, H.J. On the Polarization of Young Stellar Objects. *Astron. Astrophys.* **1978**, *70*, L3–L6.
35. Natta, A.; Prusti, T.; Neri, R.; Wooden, D.; Grinin, V.P.; Mannings, V. A reconsideration of disk properties in Herbig Ae stars. *Astron. Astrophys.* **2001**, *371*, 186–197.
36. Dullemond, C.P.; Dominik, C.; Natta, A. Passive Irradiated Circumstellar Disks with an Inner Hole. *Astrophys. J.* **2001**, *560*, 957–969. [CrossRef]
37. Appenzeller, I.; Bertout, C.; Stahl, O. Edge-on T Tauri stars. *Astron. Astrophys.* **2005**, *434*, 1005–1019. [CrossRef]
38. Grinin, V.P.; Tambovtseva, L.V.; Weigelt, G. Spectral line profiles changed by dust scattering in heavily obscured young stellar objects. *Astron. Astrophys.* **2012**, *544*, A45–A50.
39. Grinin, V.P.; Mitskevich, A.S.; Tambovtseva, L.V. Light scattering by moving dust grains in the immediate vicinity of young stars. *Astron. Lett.* **2006**, *32*, 110–119. [CrossRef]
40. Grinin, V.P.; Tambovtseva, L.V.; Dmitriev, L.V. On the spectrum of the scattered radiation of protoplanetary disks. *Astron. Rep.* **2022**, *66*, 314–320.
41. Takami, M.; Wei, Y.-J.; Chou, M.-Y.; Karr, J.L.; Beck, T.L.; Manset, N.; Chen, W.-P.; Kurosawa, R.; Fukagawa, M.; White, M.; et al. Stable and Unstable Regimes of Mass Accretion onto RW Aur A. *Astrophys. J.* **2016**, *820*, 139–152. [CrossRef]
42. Facchini, S.; Manara, C.F.; Schneider, P.C.; Clarke, C.J.; Bouvier, J.; Rosotti, G.; Booth, R.; Haworth, T.J. Violent environment of the inner disk of RW Aurigae A probed by the 2010 and 2015 dimming events. *Astron. Astrophys.* **2016**, *596*, A38–A48. [CrossRef]
43. Vink, J.S.; Drew, J.E.; Harries, T.J.; Oudmaijer, R.D.; Unruh, Y. Probing the circumstellar structures of T Tauri stars and their relationship to those of Herbig stars. *Mon. Not. R. Astron. Soc.* **2005**, *359*, 1049–1064. [CrossRef]
44. Smith, B.A.; Terrile, R.J. A Circumstellar Disk Around β Pictoris. *Science* **1984**, *226*, 1421–1424. [CrossRef] [PubMed]
45. Gledhill, T.M.; Scarrott, S.M.; Wolstencroft, R.D. Optical polarization in the disc around β Pictoris. *Mon. Not. R. Astron. Soc.* **1991**, *252*, 50–54. [CrossRef]
46. Burrows, C.J.; Stapelfeldt, K.R.; Watson, A.M.; Krist, J.E.; Ballester, G.E.; Clarke, J.T.; Crisp, D.; Gallagher, J.S., III; Griffiths, R.E.; Hester, J.J. Hubble Space Telescope Observations of the Disk and Jet of HH 30. *Astrophys. J.* **1996**, *473*, 437–451. [CrossRef]
47. Lagrange, A.-M.; Gratadour, D.; Chauvin, G.; Fusco, T.; Ehrenreich, D.; Mouillet, D.; Rousset, G.; Rouan, D.; Allard, F.; Gendron, E.; et al. A probable giant planet imaged in the β Pictoris disk. VLT/NaCo deep L'-band imaging. *Astron. Astrophys.* **2009**, *493*, L21–L25. [CrossRef]
48. Grady, C.A.; Schneider, G.; Hamaguchi, K.; Sitko, M.L.; Carpenter, W.J.; Hines, D.; Collins, K.A.; Williger, G.M.; Woodgate, B.E.; Henning, T.; et al. The Disk and Environment of a Young Vega Analog: HD 169142. *Astrophys. J.* **2007**, *665*, 1391–1406. [CrossRef]

49. Hornbeck, J.B.; Swearingen, J.R.; Grady, C.; Williger, G.M.; Brown, A.; Sitko, M.L.; Wisniewski, J.P.; Perrin, M.D.; Lauroesch, J.T.; Schneider, G.; et al. Panchromatic Imaging of a Transitional Disk: The Disk of GM Aur in Optical and FUV Scattered Light. *Astrophys. J.* **2016**, *829*, 65–81. [CrossRef]
50. Garufi, A.; Quanz, S.P.; Avenhaus, H.; Buenzli, E.; Dominik, C.; Meru, F.; Meyer, M.R.; Pinilla, P.; Schmid, H.M.; Wolf, S. Small vs. large dust grains in transitional disks: Do different cavity sizes indicate a planet?. SAO 206462 (HD 135344B) in polarized light with VLT/NACO. *Astron. Astrophys.* **2013**, *560*, A105–A115. [CrossRef]
51. Stolker, T.; Sitko, M.; Lazareff, B.; Benisty, M.; Dominik, C.; Waters, R.; Min, M.; Perez, S.; Milli, J.; Garufi, A.; et al. Variable Dynamics in the Inner Disk of HD 135344B Revealed with Multi-epoch Scattered Light Imaging. *Astrophys. J.* **2017**, *849*, 143–158. [CrossRef]
52. van Holstein, R.G.; Stolker, T.; Jensen-Clem, R.; Ginski, C.; Milli, J.; de Boer, J.; Girard, J.H.; Wahhaj, Z.; Bohn, A.J.; Millar-Blanchaer, M.A.; et al. A survey of the linear polarization of directly imaged exoplanets and brown dwarf companions with SPHERE-IRDIS. First polarimetric detections revealing disks around DH Tau B and GSC 6214–210 B. *Astron. Astrophys.* **2021**, *647*, A21–A49. [CrossRef]
53. Garufi, A.; Dominik, C.; Ginski, C.; Benisty, M.; van Holstein, R.G.; Henning, T.; Pawellek, N.; Pinte, C.; Avenhaus, H.; Facchini, S.; et al. A SPHERE survey of self-shadowed planet-forming disks. *Astron. Astrophys.* **2022**, *658*, A137–A152.
54. Safonov, B.S.; Strakhov, I.A.; Goliguzova, M.V.; Voziakova, O.V. Apparent Motion of the Circumstellar Envelope of CQ Tau in Scattered Light. *Astrophys. J.* **2022 163**, 31–42. [CrossRef]
55. Berdyugin, A.V.; Berdyugina, S.V.; Grinin, V.P.; Minikulov, N.K. Discovery of High Linear Polarization at Brightness Minima of CQ-Tauri. *Sov. Astron.* **1990**, *34*, 408–416.
56. Shakhovskoj, D.N.; Grinin, V.P.; Rostopchina, A.N. Analysis of the Historical Light Curve of the UX Ori Star CQ Tau. *Astrophysics* **2005**, *48*, 135–142 [CrossRef]
57. Eisner, J.A.; Lane, B.F.; Hillenbrand, L.A.; Akeson, R.L.; Sargent, A.I. Resolved Inner Disks around Herbig Ae/Be Stars. *Astrophys. J.* **2004**, *613*, 1049–1071. [CrossRef]
58. Chapillon, E.; Guilloteau, S.; Dutrey, A.; Piétu, V. Disks around CQ Tau and MWC 758: Dense PDRs or gas dispersal? *Astron. Astrophys.* **2008**, *488*, 565–578. [CrossRef]
59. Ubeira Gabellini, M.G.; Miotello, A.; Facchini, S.; Ragusa, E.; Lodato, G.; Testi, L.; Benisty, M.; Bruderer, S.; Kurtovic, N.T.; Andrews, S.; et al. A dust and gas cavity in the disc around CQ Tau revealed by ALMA. *Mon. Not. R. Astron. Soc.* **2019**, *486*, 4638–4654. [CrossRef]
60. Benisty, M.; Stolker, T.; Pohl, A.; de Boer, J.; Lesur, G.; Dominik, C.; Dullemond, C.P.; Langlois, M.; Min, M.; Wagner, K.; et al. Shadows and spirals in the protoplanetary disk HD 100453. *Astron. Astrophys.* **2017**, *597*, A42–A53. [CrossRef]
61. Pinilla, P.; Benisty, M.; de Boer, J.; Manara, C.F.; Bouvier, J.; Dominik, C.; Ginski, C.; Loomis, R.A.; Sicilia Aguilar, A. Variable Outer Disk Shadowing around the Dipper Star RXJ1604.3-2130. *Astrophys. J.* **2018**, *868*, 85–99. [CrossRef]
62. Casassus, S.; Avenhaus, H.; Pérez, S.; Navarro, V.; Carcamo, M.; Marino, S.; Cieza, L.; Quanz, S.P.; Alarcon, F.; Zurlo, A.; et al. An inner warp in the DoAr 44 T Tauri transition disc. *Mon. Not. R. Astron. Soc.* **2018**, *477*, 5104–5114. [CrossRef]
63. Shakura, N.I.; Sunyaev, R.A. Black holes in binary systems. Observational appearance. *Astron. Astrophys.* **1973**, *24*, 337–355.
64. Kenyon, S.J.; Hartmann, L. Spectral Energy Distributions of T Tauri Stars: Disk Flaring and Limits on Accretion. *Astrophys. J. 1987*, *323*, 714–733. [CrossRef]
65. Pety, J.; Gueth, F.; Guilloteau, S.; Dutrey, A. Plateau de Bure interferometer observations of the disk and outflow of HH 30. *Astron. Astrophys.* **2006**, *458*, 841–854. [CrossRef]
66. Wood, K.; Wolk, S.J.; Stanek, K.Z.; Leussis, G.; Stassun, K.; Whitney, B.; Wolff, M.; Whitney, B. Optical Variability of the T Tauri Star HH 30 IRS. *Astrophys. J.* **2000**, *542*, L21–L24. [CrossRef]
67. Durán-Rojas, M.C.; Watson, A.M.; Stapelfeldt, K.R.; Hiriart, D. The Polarimetric and Photometric Variability of HH 30. *Astrophys. J.* **2009**, *137*, 4330–4338. [CrossRef]
68. Stapelfeldt, K.R.; Watson, A.M.; Krist, J.E. A Variable Asymmetry in the Circumstellar Disk of HH 30. *Astrophys. J.* **1999**, *516*, L95–L98. [CrossRef]
69. Hartigan, P.; Morse, J. Collimation, Proper Motions, and Physical Conditions in the HH 30 Jet from Hubble Space Telescope Slitless Spectroscopy. *Astrophys. J.* **2007**, *660*, 426–440. [CrossRef]
70. Dyda, S.; Lovelace, R.V.E.; Ustyugova, G.V.; Lii, P.S.; Romanova, M.M.; Koldoba, A.V. Asymmetric MHD outflows/jets from accreting T Tauri stars. *Mon. Not. R. Astron. Soc.* **2015**, *450*, 481–493. [CrossRef]
71. Lee, C.-F.; Ho, P.T.P.; Li, Z.-Y.; Hirano, N.; Zhang, Q.; Shang, H. A rotating protostellar jet launched from the innermost disk of HH 212. *Nat. Astron.* **2017**, *1*, 152L–175L. [CrossRef]
72. Luhman, K.L.; Adame, L.; D'Alessio, P.; Calvet, N.; McLeod, K.K.; Bohac, C.J.; Forrest, W.J.; Hartmann, L.; Sargent, B.; Watson, D.M. Hubble and Spitzer Observations of an Edge-on Circumstellar Disk around a Brown Dwarf. *Astrophys. J.* **2007**, *666*, 1219–1225. [CrossRef]
73. Madlener, D.; Wolf, S.; Dutrey, A.; Guilloteau, S. The circumstellar disk of HH 30. Searching for signs of disk evolution with multi-wavelength modeling. *Astron. Astrophys.* **2012**, *543*, A81–A95. [CrossRef]
74. Louvet, F.; Dougados, C.; Cabrit, S.; Mardones, D.; Ménard, F.; Tabone, B.; Pinte, C.; Dent, W.R.F. The HH30 edge-on T Tauri star. A rotating and precessing monopolar outflow scrutinized by ALMA. *Astron. Astrophys.* **2018**, *618*, A120–A148. [CrossRef]

75. Whitney, B.A.; Hartmann, L. Model Scattering Envelopes of Young Stellar Objects. I. Method and Application to Circumstellar Disks. *Astrophys. J.* **1992**, *395*, 529–539. [CrossRef]
76. Whitney, B.A.; Hartmann, L. Model Scattering Envelopes of Young Stellar Objects. II. Infalling Envelopes. *Astrophys. J.* **1993**, *402*, 605–622. [CrossRef]
77. Rostopchina, A.N. The location of UX Ori stars on the Hertzsprung-Russell diagram. *Astron. Rep.* **1999**, *43*, 113–118.
78. Voshchinnikov, N.V.; Grinin, V.P.; Kiselev, N.N.; Minikulov, N.K. Dust around Young Stars: Observations of the Polarization of UX Orionis in Deep Minima. *Astrophysics* **1988**, *28*, 182–193. [CrossRef]
79. Pontoppidan, K.M.; Dullemond, C.P.; Blake, G.A.; Evans, N.J., II; Geers, V.C.; Harvey, P.M.; Spiesman, W. Modeling Spitzer Observations of VV Ser. II. An Extended Quantum-heated Nebula and a Disk Shadow. *Astrophys. J.* **2007**, *656*, 991–1000. [CrossRef]
80. Rostopchina, A.N.; Grinin, V.P.; Shakhovskoi, D.N. Photometry and Polarimetry of the Classical Herbig Ae Star VV Ser. *Astron. Rep.* **2001**, *45*, 51–59. [CrossRef]
81. Grinin, V.P.; Kolotilov, E.A.; Rostopchina, A.N. Dust around young stars. Photopolarimetric observations of the T Tauri star BM Andromedae. *Astron. Astrophys.* **1995**, *112*, 457–473.
82. Grinin, V.P.; Kiselev, N.N.; Minikulov, N.K. Observations of Zodiacal Light around the Isolated Herbig Ae-Star BF-Orionis. *Sov. Astron. Lett.* **1989**, *15*, 448–452.
83. Shakhovskoi, D.N.; Rostopchina, A.N. Photometry of the Herbig Ae Star VV Ser B in an Anomalously Deep Brightness Minimum. *Astrophysics* **2000**, *43*, 487–489. [CrossRef]
84. Rostopchina, A.N.; Shakhovskoi, D.N. Interstellar polarization in a molecular cloud in Serpens. *Astrophysics* **2000**, *43*, 289–294. [CrossRef]
85. Rodrigues, C.V.; Sartori, M.J.; Gregorio-Hetem, J.; Magalhaes, A.M. The Alignment of the Polarization of Herbig Ae/Be Stars with the Interstellar Magnetic Field. *Astrophys. J.* **2009**, *698*, 2031–2035. [CrossRef]