DUST AROUND HERBIG AE STARS: ADDITIONAL CONSTRAINTS FROM THEIR PHOTOMETRIC AND POLARIMETRIC VARIABILITY

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ABSTRACT. For the Herbig Ae stars with Algol-like minima (UX Ori, WW Vul, etc), the effects of circumstellar dust include: excess infrared emission, anomalous ultraviolet extinction, the "blueing" of the stars in minima accompanying by an increase of intrinsic polarization. Using a Monte-Carlo code for polarized radiation transfer we have simulated these effects and compared the results obtained for different models with the observational data available. We found that the photometric and polarimetric behaviour of the stars provided essential additional constraints on the circumstellar dust models. The models with spheroidal shell geometry and compact (non-fluffy) dust grains do not appear to be able to explain all the data.

1. INTRODUCTION

The dust in the vicinity of Herbig Ae stars (HAe) is responsible for the majority of the observational manifestations of the objects — *excess emission* in the infrared (IR), *anomalous extinction* in the ultraviolet (UV) and visual, and *intrinsic polarization* — and is thought to be a possible source material for the formation of planetesimals and planets. For a numerous group of HAe stars with large (up to 2 mag) brightness variations (UX Ori, WW Vul, etc.), *the "blueing" effect* in the color-magnitude diagrams (CMD) and *the increase of the intrinsic polarization* are also observed in deep minima.

The best studied objects of this group are BF Ori, UX Ori, WW Vul, and CQ Tau. Table 1 gives some observed parameters of the stars: visual magnitude in the bright states (m), the range of the brightness falls (Δm_{max}), the polarization degree in the bright (P_b) and faint (P_f) states, and the degree of interstellar polarization (P_{IS}).

To simulate the observational effects mentioned above we apply spheroidal models of the shell. Our main intention here is to examine whether such models are able to account for the data available for the stars.

2. SHELL MODEL

The dusty envelope is assumed to be an oblate spheroid with a power-law density distribution

$$n(\vec{r}) \propto \left(r_x^2 + r_y^2 + r_z^2 \, \frac{a^2}{b^2} \right)^{-\alpha/2} , \tag{1}$$

where a and b are the semiaxes of the shell (so that the isodenses are ellipses).

The dust-free innermost spherical region around the star is adopted to be due to evaporation of the grains. The outer radius of the shell has little effect on the results and is chosen large enough to be not in conflict with the observed far-IR flux.

The dust grain model is a MRN-like one: a mixture of silicate and graphite spherical grains having a power-law size distribution $n(a) = n_0 \, a^{-q}$ with the minimum and maximum radii a_{min} and a_{max}.

We believe that the photometric and polarimetric variability of the objects is caused by the dense dust clumps orbiting the stars and screening them from the observers (Grinin, 1988). It is assumed that the clumps do not affect spectral energy distribution (SED) and other characteristics of the objects significantly.

For modelling of the observational data listed in Sect. 1, we use a 2D Monte-Carlo code (Fischer, 1995). To derive the dust temperature distribution for the Monte-Carlo simulations, spherical shells of the same volume are considered with a 1D radiation transfer code (Men'shchikov & Henning, 1996).

3. RESULTS AND DISCUSSION

At first, we have considered the SED's in the IR and the stellar tracks in the CMD's and restricted the set of the models fitting both types of the data. Such a procedure gives the reliable estimates of the optical thickness of the shells τ_{sh} (Krivova, 1996). The obtained values of τ_{sh} are presented in Table 1.

The observed polarization of the stars with the shells presumably involves three components: the interstellar polarization $\vec{P}_{IS}$, the polarization caused by optical dichroism of the shell $\vec{P}_{CS}$, and the polarization due to light scattering in the non-spherical shell $\vec{P}_{sh}$ (see e. g. Berdiugin et al., 1990). For the "variable circumstellar extinction" model accepted, the polarization at given wavelength should vary with brightness variations as follows:

$$\vec{P}(\Delta m) = \vec{P}_{\mathrm{IS}} + \vec{P}_{sh} \frac{I_{sh}}{I_0 \cdot 10^{-0.4\Delta m}} + \vec{P}_{CS} \left(1 - \frac{I_{sh}}{I_0 \cdot 10^{-0.4\Delta m}} \right) , \tag{2}$$

where Δm is the stellar brightness decrease, I_{sh} is the flux of the scattered radiation, and $I_0 = I_* \exp(-\tau_{sh}) + I_{sh}$ is the total flux of the object (star+envelope) at the maximum brightness level.

The ratio I_{sh}/I_0 can be estimated as the maximum brightness fall is limited by the scattered light

$$(\Delta m)_{max} \leq -2.5 \log \frac{I_{sh}}{I_0} . \tag{3}$$

Table 1 Observational characteristics of the stars and derived parameters of the models

Star	BF Ori	UX Ori	WW Vul	CQ Tau
m, mag	∼9.5	∼9.6	∼10.2	∼9.5
$(\Delta\, m)_{max}$	3.0	2.7	2.4	1.8
$P_b, \%\ \ (m)$	0.2 (9.82)	0.7 (9.86)	0.6 (10.25)	2.7 (9.48)
$P_f, \%\ \ (m)$	5.1 (12.15)	7.2 (12.12)	5.9 (12.26)	6.7 (11.25)
$P_{IS}, \%$	0.5	0.5	0.7	1.5
τ_{sh}	0.2	0.3	0.3	0.7
I_{sh}/I_0	≤0.06	≤0.08	≤0.10	≤0.19
$P_{sh}, \%$	7.6	8.8	7.7	7.4
$P_{CS}, \%$	1.0	0.8	1.2	2.8
Λ	∼0.2	∼0.2	∼0.3	>0.2

Note: all values for the optical wavelength

Taking for $(\Delta m)_{max}$ the maximum difference between the ever observed values, we arrive at an upper limit for the ratio I_{sh}/I_0 (see Table 1). For $(\Delta m)_{max}$ as large as 2^m, this limit provides a good approximation to the ratio.

Having the polarimetric and photometric measurements for two brightness levels, the estimates of $\vec{P}_{IS}$ from the literature and of I_{sh}/I_0 from the above consideration, we can evaluate the components $\vec{P}_{CS}$ and $\vec{P}_{sh}$ (see Table 1). The former component is determined by the processes in the shells which are poorly known; our models can provide information about the latter component only.

We have calculated the intrinsic polarization $\vec{P}_{sh}$ for different models that satisfactorily explain the observed SED and the stellar tracks in the CMDs. We found that all of them gave too low polarization degree even for the shell semiaxis ratio $a/b = 5$. It should be pointed out that the polarization degree P_{sh} is known to have a maximum at $a/b \approx 5$, and the maximum mainly depends on the dust grain parameters (see e. g. Voshchinnikov and Karjukin, 1994).

On the other hand, our calculations show that the models able to fit the polarization data (with the ratio I_{sh}/I_0 given in Table 1) have the IR flux which is several times smaller than the observed one.

We see the following ways of creating a dust shell model capable to explain both the IR spectra and the polarization behaviour simultaneously:

– *A disk-like geometry.* To test this point we have considered a variant with a disk-like shell (a sphere without two cones). The polarization degree obtained was about 13% whereas the spheroidal shell with all other parameters being the same gave 6%. A possible tool for identification of the geometry of the shells can be offered by a comparison of the observational and theoretical polarization and intensity maps. Such maps have been calculated by us and will be discussed elsewhere.

– *"Fluffiness" of dust particles.* There is some evidence that the dust grains around young stars may differ from the MRN-like ones (see e.g. Greenberg & Li, 1996). Perhaps, the following may be considered as another indication. For the objects under consideration, the optical thickness $\tau_{sh} < 1$. It is well known that for $\tau_{sh} < 0.3$–0.5 the following simple relation is kept (see e. g. Voshchinnikov and Karjukin, 1994)

$$\frac{I_{sh}}{I_*} \approx \tau_{sh}\Lambda, \tag{4}$$

where Λ is grain albedo. The Λ values obtained from Eq. (4) (see Table 1) show that the albedo is rather low and typical of fluffy grains. Unfortunately, in contrast to the "compact" dust particles adopted here the grain fluffiness adds several unknown model parameters while we have already too many free parameters and too few observational constraints.

4. CONCLUSIONS

– The behaviour of the brightness and polarization of the UX Ori-like stars during their minima provides essential constraints on the circumstellar dust models.
– The models with the spheroidal shell and compact ("non-fluffy") dust particles cannot explain all the observational data available for the HAe stars with Algol-like minima.
– The models with a disk-like geometry of the shell and/or with fluffy grains could remove the problem. High-resolution polarization maps could provide a critical test for the shell geometry.

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