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Dust Shells around Herbig Ae/Be Stars with Algol-Like Minima: Modeling of Photometric Observations

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Abstract—The model of a spherically symmetric dust shell with a radial power-law distribution of matter and with clouds that obscure the star from an observer is used to simultaneously interpret the energy distribution over the range from approximately 0.3 to 100 μm and the behavior of the *U–B*, *B–V*, *V–R*, and *V–I* colors during deep photometric mininima of five Herbig Ae/Be stars: UX Ori, WW Vul, BF Ori, VX Cas, and NX Pup. The parameters of their shells and the mean albedo of dust particles in the inner parts of the shells are estimated. The derived albedos are 0.3–0.4 in *U*, *B*, and *V*. They differ markedly from the values typical of interstellar dust grains (0.6–0.7).

1. INTRODUCTION

Herbig Ae/Be stars are young stars surrounded by shells of gas and dust. They are the precursors of β Pic stars around which circumstellar dust disks have been detected and planets are thought to be forming or have been formed.

Dust particles in the vicinity of Herbig Ae/Be stars absorb, reradiate, and scatter the emission from the star (and the shell). This manifests itself in several observed effects, whose analysis yields information on the circumstellar dust. In general, only the visible and infrared (IR) spectral energy distribution of an object is modeled (see, e.g., Berrilli *et al.* 1992; Hillenbrand *et al.* 1992; Mannings 1994). Occasionally, data on the circumstellar extinction in the ultraviolet (UV) and on the profile of the dust band at λ 10 μm are invoked. This allows a slightly deeper analysis to be performed (see, e.g., Sorrell 1990; Hartmann *et al.* 1993).

Herbig Ae/Be stars with Algol-like minima (UX Ori, CQ Tau, WW Vul, etc.), which are also called UX Ori stars, offer another possibility for studying their dust shells. An important distinguishing feature of these stars is the so-called "bluing" effect which shows up during deep (normally greater than 1^m–$1\overset{m}{.}5$) minima: The color indices of a star first increase and then decrease; the color of the star may become even bluer than that at maximum light (Götz and Wenzel 1968; Zaitseva 1973). Currently, the most popular explanation for this effect is as follows (The 1994; Herbst *et al.* 1994): The minima of the star are caused by dense circumstellar clouds that obscure it from an observer, and the bluing of the star results from an increase in the fraction of the emission scattered by circumstellar dust grains distributed over the shell. This hypothesis (Wenzel 1969; Grinin 1988) was confirmed by the observations of a considerable increase in the linear polarization of starlight during minima [see Grinin (1994) and the references therein]. Clearly, within the context of this assumption, the color behavior during minima is attributed to the properties of circumstellar dust in the inner parts of the shells. The same layers are also responsible for the near- and mid-IR radiation of the objects.

Nevertheless, until now the shells around Herbig Ae/Be stars have been studied by modeling either the spectral energy distribution (Berrilli *et al.* 1992; Hillenbrand *et al.* 1992; Hartmann *et al.* 1993), including also UV circumstellar-extinction curves (see, e.g., Voshchinnikov *et al.* 1993), or the color–magnitude diagrams (and linear-polarization variations) for UX Ori stars (Voshchinnikov *et al.* 1988; Voshchinnikov 1989; Voshchinnikov and Grinin 1991). The goal of this paper is to simultaneously interpret the observed spectral energy distribution and the color–magnitude diagrams for several UX Ori stars. The observational data are described in Sec. 2. The shell model and the method of calculation are considered in Sec. 3. The results of the calculations are discussed in Sec. 4, and the main conclusions are summarized in Sec. 5.

2. OBSERVATIONAL DATA

We chose several UX Ori stars with known spectral energy distributions in the range 0.3 to 25–100 μm, in which the bluing effect was observed: UX Ori, WW Vul, BF Ori, VX Cas, and NX Pup. Some of the parameters of these stars are given in Table 1: the *V* magnitude in a bright state, the greatest observed dimming $(\Delta V)_{max}$, the spectral type, the luminosity in solar units $L_*/L_\odot$, the effective temperature of the star T_*, its dis-

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Table 1. Basic parameters of the stars under consideration

Parameters	UX Ori	WW Vul	BF Ori	VX Cas	NX Pup
V, mag.	~9.6	~10.2	~9.5	~10.9	~9.3
$(\Delta V)_{\max}$, mag.	~2.7	~2.4	~3.0	~1.7	~1.7
Spectral type	A2–3 [4]; A2 [24]	A0–3 [16]; A0 [25]	A0–F [26]; A2 [31]; A5 [15]	A0 [12]	A0 [24]
$L/L_{\odot}$	65 [4]	80 [25]	60 [31]	100 [12]	100 [24]
T^*, K	9000	9500	9500	10000	10000
D, pc	450 [4.24]	550 [25]	400 [29]	750 [1.29]	450 [24]
E_{B-V}, mag.	0.16	0.35	0.15	0.3	0.5
Visible and IR photometry	[6, 8, 15, 18]	[6, 8, 17, 18, 20]	[6, 8, 15, 19, 26, 27]	[2, 6, 8, 17]	[5, 6, 22, 24]
Photometric variability	[7, 10, 15, 17, 26, 27, 28]	[3, 11, 14, 23, 28]	[9, 15, 26, 27, 28, 30]	[2, 13, 21, 28, 30]	[5, 24]

Note: [1] Artyukhina 1960; [2] Berdyugin 1992; [3] Berdyugin *et al.* 1992; [4] Bibo and The 1990; [5] Brand *et al.* 1983; [6] Weaver and Jones 1992; [7] Voshchinnikov *et al.* 1988; [8] Glass and Penston 1974; [9] Grinin *et al.* 1989; [10] Zaitseva 1973; [11] Zaitseva 1983; [12] Zaitseva 1986; [13] Kardopolov and Filip'ev 1985a; [14] Kardopolov and Filip'ev 1985b; [15] Kilkenny *et al.* 1985; [16] Kolotilov 1977; [17] Kolotilov *et al.* 1977; [18] Cohen 1973a; [19] Cohen 1973b; [20] Li *et al.* 1994; [21] Pugach 1979, 1983; [22] Reipurth 1983; [23] Timoshenko and Filip'ev 1983; [24] Tjin A Djie *et al.* 1984; [25] Friedemann *et al.* 1993; [26] Hutchinson *et al.* 1994; [27] Herbst *et al.* 1987; [28] Herbst *et al.* 1994; [29] Kholopov 1959; [30] Shaimieva and Shutemova 1985; [31] Shevchenko and Yakubov 1992.

tance D, and the color excess E_{B-V}. Also given in the table are the references to the papers from which we took the photometric and other data used to construct the spectral energy distributions of the stars and the diagrams that show their color variations with brightness during deep minima. We estimated the stellar temperature from the spectral type following Cohen and Kuhi (1979). Small changes in this temperature are known to affect the results of modeling of the IR spectra only slightly (Rowan-Robinson 1980; Yorke and Shustov 1981).

It should be noted that the UV spectra for several Herbig Ae/Be stars were obtained from the IUE satellite (see the list of Talavera and Verdugo 1994). These data were reduced and published only for three stars with Algol-like minima: NX Pup (Tjin A Djie *et al.* 1984), HR 5999 (Perez *et al.* 1993), and UX Ori (Grady *et al.* 1995). For NX Pup and UX Ori, they refer to dimmings. For the adopted model of variable circumstellar extinction, this implies that the circumstellar-extinction curves must be mainly determined by the properties of dust in obscuring clouds, whose analysis is beyond the scope of this paper.

We did not model the polarization observations at minima and at maxima of the stars, either. We are going to interpret these data in a subsequent paper using Monte Carlo simulations of the transfer of polarized radiation in nonspherical shells. The formulation of the problem and some preliminary results of this study were published by Krivova *et al.* (1996).

3. THE SHELL MODEL

3.1. The Model and the Method of Calculation

We chose a mixture of silicate and graphite spheres of different sizes, which is commonly used to model the dust in diffuse interstellar clouds (Mathis *et al.* 1977), as the model for dust particles. Its basic parameters are the minimum ($a_{\min}$) and maximum ($a_{\max}$) particle sizes, the exponent q in the particle size distribution $n(a) \propto a^{-q}$, and the ratio of the numbers of silicate and graphite particles n_{Si}/n_C. We calculated the optical properties of the dust particles using the Mie scattering theory and took the indices of refraction for graphite and "astronomical" silicate from Draine (1985).

It is assumed that, in addition to micron-sized particles, there may also be submicron-sized particles in the shell. The latter must be rapidly swept up by radiation pressure. So far, the presence of submicron-sized grains in the shells of Herbig Ae/Be stars has not been proven; at the same time, however, it is consistent with available observational data (see, e.g., Grady *et al.* 1995). Voshchinnikov and Grinin (1991) suggested that the source of submicron-sized grains in the inner layers of the shells could be clouds which cause the minima and which are probably destroyed near the stars. A similar scenario is proposed for β Pic stars [see, e.g., Lecavelier des Etangs *et al.* (1996) and Greenberg and Li (1996)].

We used a spherically symmetric model for the dust shell with a power-law distribution of its matter along the radius r,

$$\rho(r) = \rho_0 r^{-\alpha}. \quad (1)$$

The location of the inner boundary of the shell R_i markedly affects the near-IR flux and can be determined by comparing the calculated and observed fluxes. Note that for all the stars considered here R_i turns out to be close to the boundary beyond which the grain evaporation must occur (the temperature $T_i \approx$ 1200–1500 K). The outer radius of the shell R_0 can be estimated very roughly from the far-IR fluxes. However, its exact value does not markedly affect the modeling of the spectral energy distribution at shorter wavelengths and, consequently, of the color–magnitude diagrams.

We calculated the intensity of the radiation from the object (star+shell) using the formula

$$I_\lambda = I_\lambda^{\mathrm{Kurucz}}\left[e^{-\tau_\lambda} + \frac{I_\lambda^{\mathrm{sca}} + I_\lambda^{\mathrm{therm}}}{B_\lambda(T_*)}\right], \qquad (2)$$

where τ_λ is the optical depth of the shell, $I_\lambda^{\mathrm{Kurucz}}$ is the intensity of the stellar radiation as derived from the stellar model atmospheres of Kurucz (1979), $B_\lambda(T_*)$ is the intensity of the radiation from a blackbody with the temperature equal to the effective temperature of the star, and I_λ^{sca} and $I_\lambda^{\mathrm{therm}}$ are the intensities of the scattered and thermal radiation of the shell, respectively. We determined the change in the brightness of the object during an eclipse of the star by an obscuring cloud using standard formulas (see, e.g., Krivova 1997).

We calculated the intensities of the scattered and thermal radiation of the shell using the program of E. Kruegel (Chini *et al.* 1986), which allows a simultaneous solution of the equation of radiative transfer in a spherically symmetric shell around a blackbody source and the equation of thermal balance for dust grains.

We disregarded the possible presence in the shells of very small particles ($a < 0.005$ µm) and polycyclic aromatic hydrocarbons (PAHs) (see, e.g., Natta *et al.* 1993; Prusti *et al.* 1994), because the observations have not yet unequivocally confirmed the assumption that these particles do play a noticeable role in the shells (Brooke *et al.* 1993; Li *et al.* 1994). Note also that we ignored the free–free emission of circumstellar gas, which can be substantial, in particular, in the infrared [see Berrilli *et al.* (1992) and references therein].

3.2. *Parameters and the Main Properties of the Model*

It is well known that the observed spectral energy distribution of a source surrounded by a dust shell can be reproduced by using various shell models similar to the model described above (see, e.g., Stenholm *et al.* 1991; Thamm *et al.* 1994; Butner 1996; Men'shchikov and Henning 1996). Modeling of the color–magnitude diagrams and their comparison with observed diagrams can narrow the range of such models. However, since these diagrams (and the spectral energy distribution) have only a few independent characteristic features, only a few basic model parameters can be obtained from this comparison with observations.

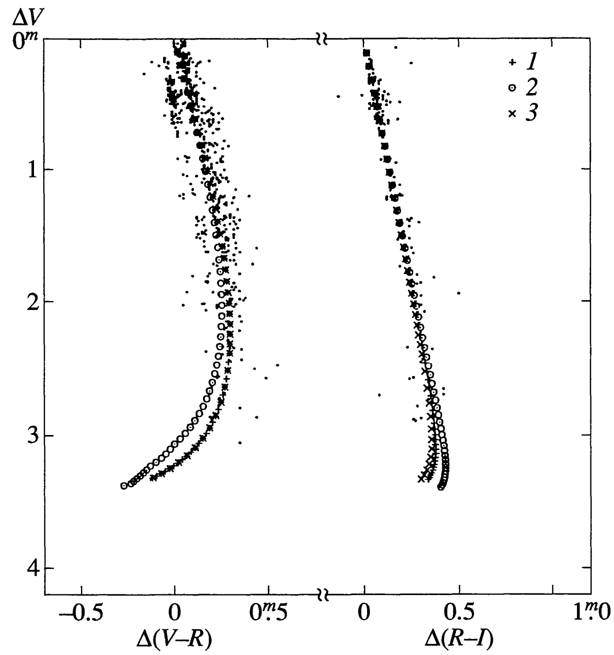

Fig. 1. The color–magnitude diagrams for shell models with the same $\tau_V^{\mathrm{sca}} = 0.08$ and close values of τ_R^{sca} and τ_I^{sca} [+, ⊙, and × denote the models with ($a_{\min}$, $a_{\max}$, q) = (0.01 µm, 1.28 µm, 4.9), (0.005 µm, 0.08 µm, 3.7), and (0.005 µm, 0.32 µm, 4.0), respectively; the dots are the observations of BF Ori].

Our model has at least eight input parameters: $a_{\min}$, $a_{\max}$, q, $n_{\mathrm{Si}}/n_{\mathrm{C}}$, α, R_i, R_0, and ρ_0 (or the dust mass in the shell M_{env} at given values of α, R_i, R_0). Let us consider the characteristic features of the modeled observational data and try to identify those combinations (functions) of input parameters[1] on which they mainly depend.

The observed **color–magnitude** diagrams (see, e.g.,) have the following basic parameters: (1) the slope of the tracks at the initial phase of brightness decline (for $\Delta V < 1^m$); (2) the position of the turning point when the bluing begins; and (3) the position of the peak ($(\Delta V)_{\max}$, $\Delta(X-Y)_{\max}$).

The slope of the tracks is associated with the properties of dust in the clouds causing eclipses (see, e.g., Friedemann *et al.* 1993, 1995); it will not be discussed below.

The maximum dimming (only the starlight scattered

[1] We have in mind such model parameters as the optical depth of the shell $\tau = \tau(a_{\min}, a_{\max}, q, n_{\mathrm{Si}}/n_{\mathrm{C}}, \alpha, R_i, R_0, \rho_0)$, the mean albedo of the dust grains $\langle\Lambda\rangle = \langle\Lambda\rangle(a_{\min}, a_{\max}, q, n_{\mathrm{Si}}/n_{\mathrm{C}})$.

by dust in the shell is observed) is

$$(\Delta m)_{\max} \approx -2.5 \log \frac{F_{\rm sh}/F_*}{\exp(-\tau_{\rm sh}) + F_{\rm sh}/F_*}, \quad (3)$$

where $F_{\rm sh}/F_*$ is the ratio of the fluxes of the scattered and stellar radiation, $\tau_{\rm sh}$ is the optical depth (absorption and scattering) of the shell with no cloud on the line of sight. For optically thin shells, and many of the shells under consideration are similar to them (see Sec. 4), expression (3) simplifies further still, because $\exp(-\tau_{\rm sh}) \approx 1$ and $(F_{\rm sh}/F_*) \approx \tau^{\rm sca} \ll 1$, where $\tau^{\rm sca}$ is the optical depth of the shell for scattering, i.e.,

$$(\Delta m)_{\max} \approx -2.5 \log \tau^{\rm sca}. \quad (4)$$

As is evident from Equation (4), the maximum bluing—the difference between the $X - Y$ color indices at maximum and at minimum $(\Delta(X - Y)_{\max})$—is related to the difference between the optical depths at the wavelengths corresponding to the bands, $\tau^{\rm sca}(\lambda_X) - \tau^{\rm sca}(\lambda_Y)$.

Thus, the shape of the color–magnitude diagrams in our model is primarily determined by the optical depth of the shell for scattering $\tau_V^{\rm sca}$. This inference is demonstrated in Fig. 1, which shows the diagrams for three models with distinctly different parameters of an ensemble of dust grains but with the same values of $\tau_V^{\rm sca}$ and similar values of $\tau_R^{\rm sca}$ and $\tau_I^{\rm sca}$.

The main properties of the spectral energy distributions of shell stars and the possibility of estimating the model parameters from them have been repeatedly discussed by various authors (Rowan-Robinson 1980; Yorke and Shustov 1981; Emerson 1988; Krivova 1997) and are not considered here. We only note that the wavelength dependence of the IR radiation from the shell makes it possible to estimate the parameters α and R_i more or less reliably. The bolometric IR luminosity of the shell depends mainly on the integral of the production of the optical depth $\tau^{\rm abs}(\nu)$ and the stellar luminosity $L_*(\nu)$ over frequency ν (for optically thin shells, the luminosity is simply equal to this integral). Therefore, for the stars under consideration, it is most sensitive to $\tau^{\rm abs}$ near the maximum of $L_*(\lambda)$, i.e., in the U, B, and V bands.

Thus, two combinations of input parameters $\tau^{\rm sca}$ and $\tau^{\rm abs}$ (in addition to α and R_i) mainly determine the shape of the spectral energy distribution and the color–magnitude diagrams which we calculated using the above assumptions. On the other hand, it appears that the simultaneous interpretation of these data must primarily aim at estimating the optical depths of the shell $\tau^{\rm sca}$ and $\tau^{\rm abs}$: the former in those bands in which the bluing effect is observed and the latter in the range 0.3–0.5 μm.

Note that for the model we chose, which assumes identical properties of the dust along the radius of a spherically symmetric shell, the mean albedo of the grains $\langle\Lambda\rangle$, which is the ratio of the scattering and absorption cross sections averaged with the corresponding particle size distribution, is equal to $\tau^{\rm sca}/(\tau^{\rm abs} + \tau^{\rm sca})$. Admittedly, the albedos thus obtained should be most likely considered as upper limits, since we performed the calculations for isotropic scattering (the asymmetry factor of the scattering diagram is $\langle\cos\theta\rangle = 0$).

For all the ensembles of dust grains we considered, $\langle\cos\theta\rangle > 0$, i.e., more radiation is scattered forward than backward. For anisotropic scattering, the number of second and subsequent scatterings must be smaller than that in our case, because in the first scattering more radiation is scattered toward the outer, more rarefied layers of the shell. Accordingly, the part of the scattered radiation that is absorbed in the second and subsequent scatterings must be smaller. Therefore, for the same parameters of the star and the shell (and, consequently, $\tau^{\rm sca}$), the total flux of the radiation scattered by the shell $F_{\rm sh}$ will exceed our calculated flux if the anisotropy of the scattering is taken into account (clearly, the discrepancy is small for nearly optically thin shells). Hence, in order to obtain, for example, the same depth of minimum, we must choose an ensemble of grains with a lower mean albedo in the visible. Our test Monte Carlo computations show that for anisotropic scattering the mean albedo must be reduced by no more than ~20%.

4. RESULTS AND DISCUSSION

By varying the model parameters, we found several models for each of the stars that satisfactorily fitted the observational data. Since some of the parameters of these shell models—the exponent (α) in the radial dust distribution, the inner (R_i) and outer (R_0) radii of the shell, its mass ($M_{\rm env}/M_\odot$), and the optical depths for absorption ($\tau^{\rm abs}$) and scattering ($\tau^{\rm sca}$) in U and V—have similar values, they are given in Table 2 only for one of the models. Figures 2–4 show that these models are consistent with the observational data for UX Ori, BF Ori, and VX Cas. The models that are consistent with the data for WW Vul and NX Pup have been previously considered by Krivova (1997) and Krivova and Il'in (1996), respectively; therefore, we do not provide the figures for these stars.

In contrast to the parameters that describe the distribution of dust in the shells, we could not unambiguously determine the parameters of the ensembles of grains. We found several methods of obtaining good agreement with the observational data. Models with the grain sizes 0.005–1 μm and the exponent $q \approx 4$–5 or with $q = 3.5$ (the standard value for the interstellar medium) but with a maximum grain size of about 0.1 μm turned out to be satisfactory in this sense (see also Krivova 1997). Agreement with the observational data was also obtained for models in which there were no particles of sizes between 0.05–0.1 and 0.3 μm (finer and coarser grains were present). Clearly, for this range of uncertainty in the grain sizes, the ratio $n_{\rm C}/n_{\rm Si}$ is of no impor-

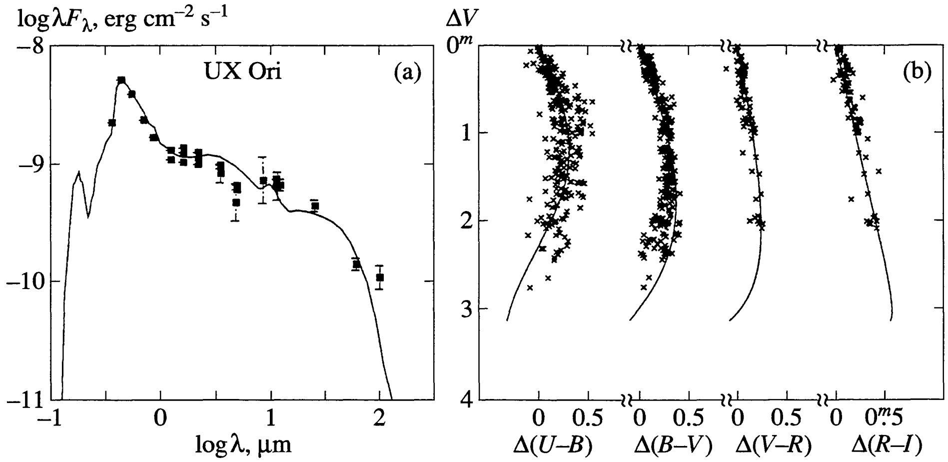

Fig. 2. (a) The spectral energy distribution and (b) the color–magnitude diagrams (b) for UX Ori (the solid line is the model from Table 2).

tance; in general, however, mixtures with $n_C/n_{Si} > 1$ have almost always been preferred.

Obviously, a common property of the above ensembles of grains is the relatively low mean albedo: either because of the greater abundance of fine grains, or because of the absence of submicron-sized particles, or because of the smaller fraction of scattering particles.

The grain albedos $\langle\Lambda\rangle$ averaged over the ensemble of particles for the U and V bands are given in Table 2. Clearly, they are considerably lower than the albedos of dust grains in interstellar clouds. The latter were estimated by several methods: by analyzing the observations of the diffuse Galactic light, reflection nebulae, and dark clouds [see, e.g., Witt *et al.* (1989) and references therein]. Although each of these methods has its drawbacks and yield albedos with an error ~0.1, they all suggest that the albedo of interstellar grains is 0.6–0.7 in U, B, and V (the asymmetry factor $\langle\cos\theta\rangle \sim 0.7$).

If we assume that clouds supply dust to the inner layers of the shell, then the processes that accompany the destruction of these clouds and the evaporation of grains could be responsible for the difference in the albedos of the interstellar and circumstellar particles. A similar scenario for β Pic stars was considered by Greenberg and Li (1996). They assumed that cometary objects continuously supply dust, which consists of porous particles with a low albedo (~0.2) similar to cometary dust, to the inner disk. These particles are exposed to radiation near the star and are partially destroyed, crystallized, etc. This assumption is based on the relatively well-studied processes that proceed in the interplanetary medium and can account for the silicate-band profiles and other observational data for β Pic stars.

Note that the color–magnitude diagrams for UX Ori and WW Vul were modeled by Voshchinnikov (1988) and Voshchinnikov and Grinin (1991). For these stars, they obtained good agreement with the observational data for (a_{min}, a_{max}, q, q, n_{Si}/n_C, A/B, τ_U^{ext}) = (0.04 μm, 0.15 μm, 3.5, 1.07, 4, 0.5) and (0.055 μm, 0.25 μm, 5.0, 0.25, 3, 0.55), respectively, where A/B is the ratio of the semiaxis of the flattened spheroidal shells under consideration. Given that the albedos of these grain mixtures are 0.74 and 0.54 and that the correction for the shell shape is $(A/B)^{2/3}$ (see Krivova 1997), it is easy to show that the scattering optical depth of spherical shells with the same volume as the spheroidal shells must be $U\ \tau_U^{sca} \approx 0.15$ in U for UX Ori and 0.16 for WW Vul, in agreement with the values in Table 2.

Finally, let us consider some of the factors (which were not included in the shell model) that could affect the estimates of the model parameters (see Table 2) and, in particular, the grain albedo.

(1) The brightenings of the stars after the entrance into a minimum and their dimmings after the emer-

Table 2. Model parameters

	UX Ori	WW Vul	BF Ori	VX Cas	NX Pup
α	1.3	1.5	1.45	1.3	1.3
R_i, AU	2.0	2.0	3.0	3.5	3.0
R_o, AU	3×10^3	10^4	10^4	2×10^3	5×10^3
$M_{env}/M_\odot$	5×10^{-6}	10^{-5}	10^{-5}	5×10^{-6}	10^{-4}
τ_U^{abs}	0.43	0.43	0.29	0.42	1.32
τ_V^{abs}	0.20	0.20	0.13	0.21	0.56
τ_U^{sca}	0.16	0.14	0.10	0.31	0.63
τ_V^{sca}	0.09	0.08	0.06	0.23	0.41
$\langle\Lambda\rangle_U$	0.27	0.25	0.26	0.42	0.29
$\langle\Lambda\rangle_V$	0.30	0.28	0.31	0.52	0.39

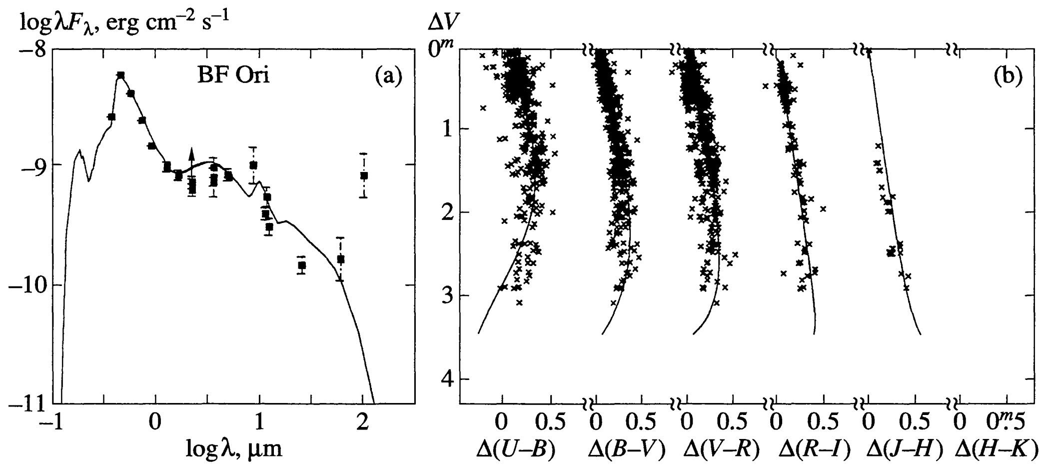

Fig. 3. The same as Fig. 2 for BF Ori.

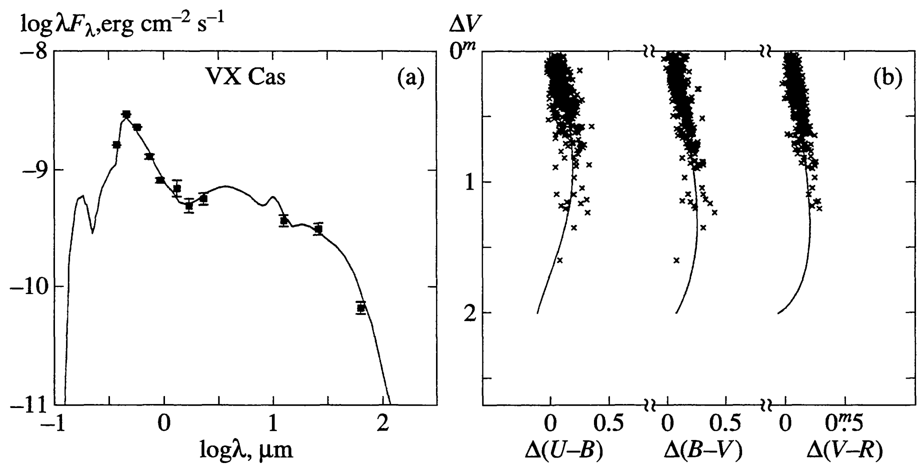

Fig. 4. The same as Fig. 2 for VX Cas.

gence from it (see, e.g., Grinin *et al.* 1991) can be explained by clumpiness of the obscuring clouds. In this case, the depth of minimum $(\Delta m)_{\max}$ can be determined not only by the scattered light but also by incomplete elimination of the direct starlight, for example, for a simple model of an inhomogeneous screen with a filling factor f. The numerator in Equation (2) must then be replaced by $[(1-f)\exp(-\tau_{sh}) + fL_{sh}/L_*]$, and the optical depth of the shell for scattering and, accordingly, the albedo must evidently be even smaller. In general, this porosity of the screen must simply "cut off" the lower part of the color–magnitude diagram. Note, however, that a brightness decline in the stars by more than 2^m suggests that the filling factor f is very close to unity ($f > 0.9$).

(2) The linear polarization in the Herbig Ae/Be stars, which reaches 7–10% at minimum light, suggests that the distribution of dust in the shells is substantially nonspherical. Until now, no final conclusion has been reached about how the circumstellar dust is distributed: in the form of a disk or a flattened shell[2] (see, e.g., Hillenbrand *et al.* 1992; Berrilli *et al.* 1992; Hartmann *et al.* 1993; Butner 1996).

In principle, flattened shells do not differ much from our spherically symmetric model. In optically thin shells the dust "emit solidly" and the relation between the grain temperature and the distance to the star depends only slightly on the geometry, for example, on the degree of flattening in the case where the isodenses are spheroids. Therefore, the results of our modeling of IR spectra must also generally hold for nonspherical shells. In this case, however, obvious corrections must be applied. In particular, the optical depths in Table 2 are the quantities averaged over all directions. Their relation to the optical depth along the line of sight, for example, for a spheroidal dust distribution depends on

[2] In terms of the observational manifestations of the shells, these distributions represent limiting cases.

the flattening of the shell and on its orientation. Clearly, the fraction of scattered radiation [or, more precisely, the quantity $\exp(-\tau_{sh}) + F_{sh}/F_*$) also depends on these parameters, especially when the anisotropy of the scattering is taken into account [see, e.g., Fig. 4 in Voshchinnikov *et al.* (1995)]. Nevertheless, the mean albedos of circumstellar grains from Table 2 must probably change only slightly.

A major difference between dust disks and shells is that their surface can be illuminated by the star, and that the optical depth along the disk radius can be fairly large. Therefore, the relation between the grain temperature and the distance to the star can differ markedly from the typical relation for spherical models. In that case, our conclusions about the radial distribution of dust (the parameters α and R_0) and the estimates of the optical depths (τ^{abs} and τ^{sca}) are invalid.

(3) The observed near-IR excesses can be explained in several ways: by the radiation of circumstellar, submicron-sized dust grains; by free–free emission [see Berrilli *et al.* (1992) and references therein]; and by the radiation of very small grains and PAHs (see, e.g., Natta *et al.* 1993). Clearly, by attributing ~50% of the near-IR luminosity to the radiation of gas and/or very small dust grains, which we ignored in our analysis, we can construct a model that describes the observations, and that includes particles with the albedo typical of interstellar dust.

A test for this model could be an analysis of the spatial distribution of the emission and the interpretation of polarization observations in the visible. High-resolution maps of the intensity and polarization distribution have been obtained so far only for a very small number of Herbig Ae/Be stars. They could be of use not only in establishing the source of excess IR emission but also in constraining the shell models further still (see, e.g., Butner 1996; Il'in *et al.* 1996).

Polarization data for maximum and minimum light are available for many UX Ori stars. The preliminary results of our Monte Carlo simulations of the polarization data, together with the spectral energy distribution and the color–magnitude diagrams for the star CQ Tau (given the anisotropic scattering for a spheroidal dust distribution), show that invoking dust grains with low albedos does account for these data and for photometric data (Krivova *et al.* 1996). Note that, by considering a single scattering in a homogeneous spheroidal shell and by modeling the color and polarization behavior at minima, Voshchinnikov (1989) also pointed out that the particles in the vicinity of UX Ori stars must have reduced albedos.

5. CONCLUSION

For five Herbig Ae/Be stars with Algol-like minima (UX Ori, WW Vul, BF Ori, VX Cas, and NX Pup), we interpreted the energy distribution over the range from approximately 0.3 to 100 μm and the behavior of the *U–B*, *B–V*, *V–R*, and *V–I* colors during deep minima of the stars. We used the model of a spherically symmetric shell with a radial power-law dust distribution and with a power-law size distribution of graphite and silicate particles.

We estimated the shell parameters (optical depths, sizes, etc.) and the ensemble-averaged albedo of circumstellar dust particles in the inner layers of the shells. The derived albedos (0.3–0.4 in *U*, *B*, and *V*) differ substantially from those typical of interstellar grains (~0.6–0.7) and are close to the values obtained by Greenberg and Li (1996) for the inner disks around β Pic stars and typical of cometary dust.

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