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VARIABLE EXTINCTION IN HD 45677 AND THE EVOLUTION OF DUST GRAINS IN PRE–MAIN-SEQUENCE DISKS

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ABSTRACT

Changes in the UV extinction and IR emission were sought in the Herbig Ae/Be star candidate HD 45677 (= FS CMa) by comparing UV, optical, and IR observations made approximately 10 yr apart. HD 45677 varied significantly, becoming more than 50% brighter in the UV and optical than it was a decade ago. A comparison of the observations between epochs indicates that if the variations are due to changes in dust obscuration, the dust acts as a gray absorber into the near-IR and must be depleted in grains smaller than 1 μm. This is similar to the results obtained on the circumstellar disks of stars like Vega and β Pic, and suggests that radiation pressure may be responsible for the small-grain depletion. In addition, the total IR flux seems to have declined, indicating a decrease in the total mass of the dust envelope that contributes to the IR emission in this part of the spectrum. Due to the anomalous nature of the extinction, the use of normal extinction curves to deredden the spectral energy distributions of stars with circumstellar dust may lead to significant errors and should be used with great caution.

Subject headings: circumstellar matter — dust, extinction — stars: emission-line, Be — stars: individual (HD 45677) — stars: pre–main-sequence

1. INTRODUCTION

Observations of pre–main-sequence stars provide a window on the formation and early evolution of stars and open the possibility of seeing the earliest phases of solar system formation. The best known group of PMS stars are probably the T Tauri stars, young objects surrounded by nebulosity, exhibiting substantial emission lines and, in many cases, IR emission due to heated circumstellar dust. Their location on the H-R diagram indicates that many are destined to evolve into stars of approximately solar spectral type.

The Herbig Ae/Be (HAEBE) stars represent the high-mass analogues of T Tauri stars. They are found in regions of recent star formation and are generally surrounded by nebulosity. All exhibit emission lines in Hα and often numerous other lines. They generally possess substantial IR emission in excess of that expected from a stellar photosphere. In many cases the 9.7 μm silicate feature is seen, so that the excess is attributed mainly to heated circumstellar dust grains.

If the T Tauri and HAEBE stars represent the last stage of star evolution prior to the main sequence, they may hold the key to understanding the IR excesses seen in a large fraction of main-sequence stars by the *IRAS* satellite (see Backman & Paresce 1992 for a recent review of these objects). The best known examples of these are Vega and β Pic.

The HAEBE stars are of particular importance in understanding these systems for two reasons. First, they are the precursors to stars like Vega and β Pic (the only star with a well-studied resolved circumstellar disk; Smith & Terrile 1984), which are hot enough (spectral types A0 and A5, respectively) to power IR excesses with small dust masses. Second, if one is interested in the physical and optical properties of the grains in these disks, being able to extend the analysis over a wide wavelength range is desirable if limits on the grain composition and size distribution are desired. The HAEBE stars are hot enough to extend the analysis into the UV, while the T Tauri stars are not.

The usual method of defining the optical properties of interstellar dust grains in the optical and UV is to divide the fluxes of the star suffering dust extinction with one of the same spectral type with little or no extinction (the so-called pair method). The result is the total extinction (absorption plus scattering) of the dust. In principle, a similar analysis of the circumstellar dust around the HAEBE stars (and other dusty stars) would yield similar information about those grains.

However, single-snapshot studies of these objects have certain inherent uncertainties that cloud the analysis of the

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optical characteristics of the dust. Their spectra (photosphere plus circumstellar gas) are often inherently different from the stars used for comparison. Many include intrinsic contaminating atomic emission and absorption that can adversely affect the derivation of the dust properties. Also, many of them suffer significant foreground extinction (due to diffuse galactic extinction as well as to nearby clouds in star-forming regions).

Variability studies of stars with circumstellar dust provide an opportunity to circumvent these problems. By comparing the star with itself at another epoch, the likelihood of a spectral match is improved. Although some changes in circumstellar gas emission and absorption may be present, it will be less than the total difference between the program star and the normal comparison star. Since the foreground extinction does not vary, its effects are eliminated in the comparison as well.

The purpose of this project was to derive the extinction characteristics of the dust grains surrounding a variable HAEBE star by comparing observations made approximately a decade apart. The first UV spectra and detailed UV extinction curves ($\lambda < 3000$ Å only) for these stars were presented by Sitko, Savage, & Meade (1981; hereafter SSM81) and Sitko, Simon, & Meade (1984) using observations obtained with the *International Ultraviolet Explorer* (*IUE*). In all cases the UV extinction was found to be different from that of the general interstellar medium and suggested a relative paucity of small grains.

One of the best candidates for a variability study is HD 45677 (= FS CMa), whose optical variability has been described by Swings & Swings (1972) and Feinstein et al. (1976). Swings & Allen (1971) suggested changes in circumstellar dust as one mechanism for the observed variations. Coyne & Vrba (1976) detected wavelength-dependent variations in the optical polarization of HD 45677 and suggested that the scattering was due to large (~ 1 μm) dust grains located in a circumstellar disk. Grains of similar size were also required to model the spectral energy distribution (Sorrell 1989). Variations in the UV are described by Savage et al. (1978) and by Sitko & Savage (1980). However, the UV data were a collection of observations with vastly different spectral resolutions from the *Astronomical Netherlands Satellite* (*ANS*) and the *IUE*, and little detailed comparative analysis was possible.

During the subsequent decade, HD 45677 was monitored photometrically, and it exhibited fluctuations in optical light of up to 0.6 mag (Halbedel 1989). Its polarization was studied by Schulte-Ladbeck et al. (1992) from IR through the UV (the latter using the Wisconsin Ultraviolet Photopolarimeter Experiment [WUPPE] on the *ASTRO-1* mission), who confirmed, and extended Coyne & Vrba's model for the dust geometry. Grady et al. (1993), using high-resolution *IUE* spectra, also detected evidence for gas inflow and suggested it was a previously unrecognized HAEBE star.

To summarize, HD 45677 appears to be a star undergoing accretion of circumstellar matter which is located in a disk or torus, which has dust grains which seem to be rather larger than "normal" interstellar dust, and where variations in dust obscuration occur. It shares many characteristics of the HAEBE stars, but is not associated with nebulosity.

The key to understanding HD 45677 and related objects is simultaneous observations from the UV, where the dust absorbs and scatters light, through the IR, where it re-emits its absorbed energy. If at all possible, the observations should be made with similar detectors, to minimize systematic differences between epochs.

2. OBSERVATIONS

The observations for this project were obtained on a variety of dates and with a number of different telescopes and detectors. The dates of the observations used with each instrument are summarized in Table 1.

2.1. *UV Observations*

For this project, the UV data for both epochs were obtained with the *IUE* satellite. For $\lambda < 0.2$ μm, the SWP camera was used for both epochs (1980 and 1992). For $\lambda > 0.2$ μm, the LWR camera was used for the first epoch, while the LWP had become the standard camera by the second epoch. However, the relative sensitivities of the two cameras are fairly well calibrated, as is the sensitivity of SWP.

In order to insure the photometric stability of the UV system, a few of the extinction comparison stars used by SSM81 were also reobserved. No significant changes in the extracted fluxes of these stars longward of 1300 Å were observed. Some changes at shorter wavelengths were seen, and the nature of these differences are not known. However, since we are confining the analysis to longer wavelengths, this does not affect our conclusions.

2.2. *Optical Observations*

The low-resolution spectrophotometer (LRSP; $\Delta\lambda = 40$ Å) of the Pine Bluff Observatory was used for the earlier optical observations (SSM81). However, this instrument could not be used for the latter epoch, since it was decommissioned years ago. To compare with other optical observations, the LRSP data were converted to *UBV* magnitudes by convolving the measurements with the *UBV* filter transmissions, which were used for the second-epoch observations. These observations were obtained with two ground-based telescopes.

The 0.6 m telescope at Mount Laguna Observatory,

TABLE 1

HD 45677 DATES OF OBSERVATIONS

INSTRUMENT	WAVELENGTH (μm)	EPOCH-1 DATE 1980 UT	EPOCH-1 DATE JD = 2,440,000 +	EPOCH-2 DATE 1992 UT	EPOCH-2 DATE JD = 2,440,000 +
IUE	0.12–0.33, 0.55	Feb 21	4290	Feb 26	8678
PBO LRSP	0.34–0.58	Jan 23	4261		
Mount Laguna Obs.	0.36–0.55			Feb 24	8676
Corralitos Obs.	0.44–0.55			March 13	8694
KPNO InSb	1.25–3.5			Feb 29	8681
KPNO Bolo	2.25–19	Jan 3	4241	Feb 15	8667
Mount Lemmon Bolo	1.25–19			March 25	8706

equipped with a thermoelectrically cooled Hamamatsu gallium-arsenide (GaAs) photomultiplier tube, was used to obtain Johnson-Morgan *UBVRI* data on 1992 February 24. Data from the standard stars revealed probable errors in the acquisition of the IR data, which was most likely a result of photometric leakage in the IR. These (*RI*) data have been excluded from the analysis.

The 0.6 m telescope of the Corralitos Observatory has observed a number of HAEBE and similar stars in *V* and *B*, including HD 45677, for many years, and these data were also used as part of this study. Two different photometric systems have been used: one based on an EMI 9924A tube and the second on an R4457. Extreme care was taken to insure that there were no transformation errors between the two systems.

The Fine Error Sensor (FES) of the *IUE* satellite was also used to obtain *V* magnitudes along with the UV spectra. The calibration of the FES has been frequently updated throughout the lifetime of the *IUE*.

In order to place all of the optical data on the same zero-point system, the ground-based *V* observations were shifted by small amounts to agree with the *V* magnitudes of the FES, which was the only optical system common to both epochs. The merged optical data are given in Table 2.

2.3. *IR Observations*

The Kitt Peak bolometer "BOLO" was used on the 1.3 m telescope for both epochs from 2.2 μm to 10 or 20 μm (the latter epoch being its last observation before decommissioning by KPNO). For both epochs the same photometric system and standard stars were used (primarily α Tau), in order to minimize systematic effects between epochs. The bolometer uses a fixed aperture of 1 mm, corresponding to 11″ on the 1.3 m telescope. Observations were made on 1980 January 3 and 1992 February 15. Observations were reduced on the KPNO IR photometric system.

Additional IR observations of HD 45677 were obtained on 1992 March 25 at the Mount Lemmon Observing Facility 1.5 m telescope using a GeGa bolometer. The bolometer was equipped with *J*, *H*, *K*, *L*, *M*, *N*, 18 μm filters, and in addition, a set of six narrowband filters spanning the 9.7 μm silicate feature region from 7.8 μm to 12.5 μm. Tokunaga et al. (1986) describe these narrowband silicate features, and a discussion of the bolometer, as well as the photometric system and calibration, is given by Gehrz, Hackwell, & Jones (1974) and Gehrz, Grasdalen, & Hackwell (1987). The chopping beam throw was 45″ and beam size was 15″. β Gem served as the calibration star and was observed both immediately prior to and after HD 45677. The errors on all measurements were 0.05 mag. Many of the filters in this bolometer have different effective wavelengths than the Kitt Peak system, so that the observations of the two systems could not be averaged at longer wavelengths.

TABLE 2

HD 45677 MAGNITUDES AND DIFFERENCES

λ (μm)	*m*(1980)	*m*(1992)	Δ*m*(1992–1980)
0.36	+7.96	+7.44	−0.52
0.44	+8.60	+8.10	−0.50
0.55	+8.64	+8.04	−0.60
1.25	+7.70	+7.15	−0.55
1.65	+6.64	+6.24	−0.40
2.25	+4.57	+4.60	+0.03
3.5	+2.25	+2.29	+0.04
4.6	+0.85	+0.98	+0.13
7.8		−0.29	
8.4	−1.10	−0.70	+0.40
8.7		−1.05	
9.5	−1.54	−1.11	+0.43
9.8		−1.36	
10.1	−1.61	−1.35	+0.26
10.3		−1.49	
11.0	−1.82	−1.50	+0.32
11.6		−1.93	
12.5	−1.90	−1.60	+0.30
19	−2.96	−2.50	+0.46

The 1992 February observations were obtained using the KPNO 1.3 m telescope equipped with a single-channel InSb detector (OTTO) and KPNO standard *JHKL* wideband filters. Sky transparency was good early in the evening when these observations were obtained. Extinction coefficients for the night of 29 February were derived from eight points in *JHK* and five in *L*. Transformation coefficients were derived for the observing run using 22 points at *JHK* and five points at *L*.

The IR data from all three systems are listed in Table 2, where we have averaged the *JHKL* observations for 1992. The rms differences between the observations were 0.04 mag, 0.06 mag, 0.15 mag, and 0.07 mag at *J*, *H*, *K*, and *L*, respectively.

3. FLUX VARIATIONS

HD 45677 has dutifully gotten considerably brighter at both optical and UV wavelengths since the original *IUE* observations reported by SSM81.

Halbedel (1989, 1991) has reported some of the previous optical variations. Figure 1*a* shows the *V* and *B*−*V* behavior for the past decade. Both short- and long-term changes are apparent. Two large maxima in *V* are recorded, separated by approximately 1500 days. In addition, the earlier long-term maximum is also characterized by shorter quasi-periodic changes with a timescale of about 297 days. This behavior appears to have diminished during the more recent maximum. Changes in *B*−*V* are less than 0.1 mag, but the star seemed to be systematically bluer during the recent bright phase compared to earlier fainter phases (see Fig. 1*b*).

The *IUE* spectra of HD 45677 for the epochs considered are shown in Figure 2. The uppermost spectrum is that taken in 1992 and is considerably above that of the earlier epochs, which are also characterized by lower visual fluxes (see Figure 1). This is precisely the behavior expected if changes in the line-of-sight extinction were taking place.

The change in the optical and IR magnitudes are listed in Table 2.

4. DUST EXTINCTION AND GRAIN PROCESSES

4.1. *UV-Optical Variability*

By carefully comparing the brightness of the star in each observed wave band, it was possible to construct a pair-method magnitude-difference curve from the fluxes at two flux states. For the low-flux states, the three lowest *IUE* spectra were coadded, since they were indistinguishable. For the high-flux state, the 1992 observations were used. Figure 3 shows the difference in magnitude of the *IUE* and the *UBVJHK* data for the two epochs. Wavelengths longer than these are dominated by thermal emission and are not included.

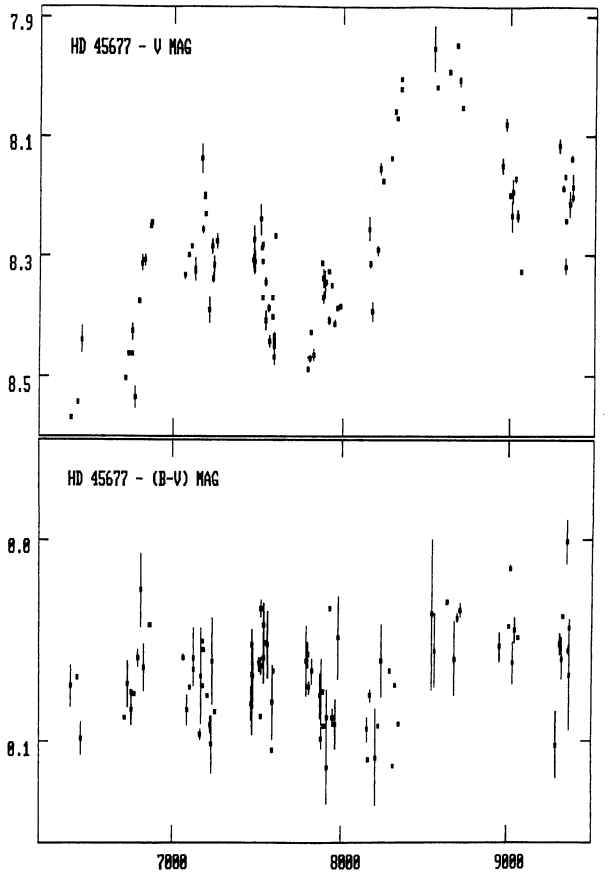

FIG. 1*a*

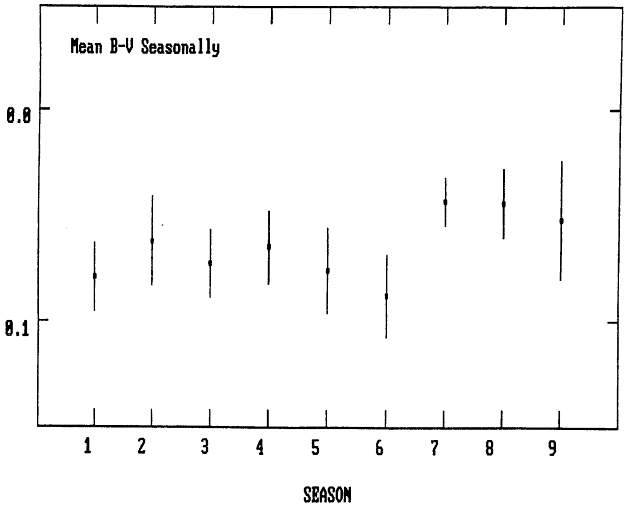

FIG. 1*b*

FIG. 1.—(*a*) V and $B-V$ light curves for HD 45677, monitored at the Corralitos Observatory, for the past decade. (*b*) Seasonal mean values for $B-V$.

While the flux change observed could be due to changes in the effective temperature of the star, we consider this unlikely for two reasons. First, changing the global temperature produces a change in flux that is more wavelength dependent than what was observed in HD 45677. For comparison, in Figure 3 we also show the ratio of flux computed from model atmospheres of stars whose effective temperatures are 20,000 K and 22,500 K (Kurucz 1979), close to the effective temperature of HD 45677. To reproduce the observations, a range of temperatures is required, with significantly greater flux produced at lower temperatures. Second, and more important, while the optical and UV flux *increased*, the IR emission *decreased*. If the IR emission is due to dust heated by the star, an increase in stellar luminosity would increase the IR emission, not decrease it.

We therefore believe that the observed flux changes are produced by changes in the obscuration of the dusty envelope around the star.

One potential problem with determining the extinction characteristics of any circumstellar envelope is that the results can be dependent on the geometry of the surrounding dust cloud. Extinction is due to the combined removal of photons from the line of sight by both scattering, which simply redirects the photon, and true absorption, which destroys it. For a spherically symmetric cloud included entirely within the entrance aperture of the observing instrument, every photon scattered out of the line of sight is replaced by another scattered into it. If the mean free path of photons in the cloud at that wavelength is comparable to or larger than the physical size of the cloud itself, scattering has little effect, and one measures only absorption. If the mean free path is smaller than the size of the cloud, the extinction is affected by both, since scattering increases the path the photon travels in the cloud, increasing the likelihood it will get absorbed. Even then, however, the net extinction is not equivalent to what is measured in the interstellar medium (Code 1973).

If the geometry of the dust is disklike and seen nearly edge-on, as has been suggested by Schulte-Ladbeck et al. and Grady et al., however, then photons scattered out of the disk into the polar direction are lost to the line of sight and not "replaced" by nearly as many photons scattered into the beam. Hence, what one measures is more analogous to true extinction. To first order, we will assume that this is the case here.

In general, the extinction by small dust grains increases with decreasing wavelength until the wavelength is smaller than the grain size. At yet smaller wavelengths, the extinction becomes nearly independent of wavelength (see Bohren & Huffman 1983 for an extensive description of extinction due to small particles, or Whittet 1992 for a brief one). The extinction due to dust in the general interstellar medium is probably due to an ensemble of particles of varying sizes. Mathis, Rumpl, & Nordsieck (1977) successfully modeled the interstellar extinction curve using graphite and silicate grains with a power-law size distribution and maximum and minimum grain sizes. Steenman & Thé (1989, 1991) show that when such a size distribution is altered by adding larger grains or removing smaller ones, the extinction becomes "grayer" and anomalous circumstellar extinction curves like those reported by SSM81 can result.

In the present case, if the observed flux ratio is interpreted as due to a change in the extinction, then the grains are extremely gray down to a wavelength of 1.6 μm (the data longward of that point are dominated by thermal emission so that changes in the extinction of the stellar photospheric light are simply overwhelmed by the thermal emission of the dust). This requires that most of the grains smaller than this have been depleted in the cloud. We note, however, that an extremely

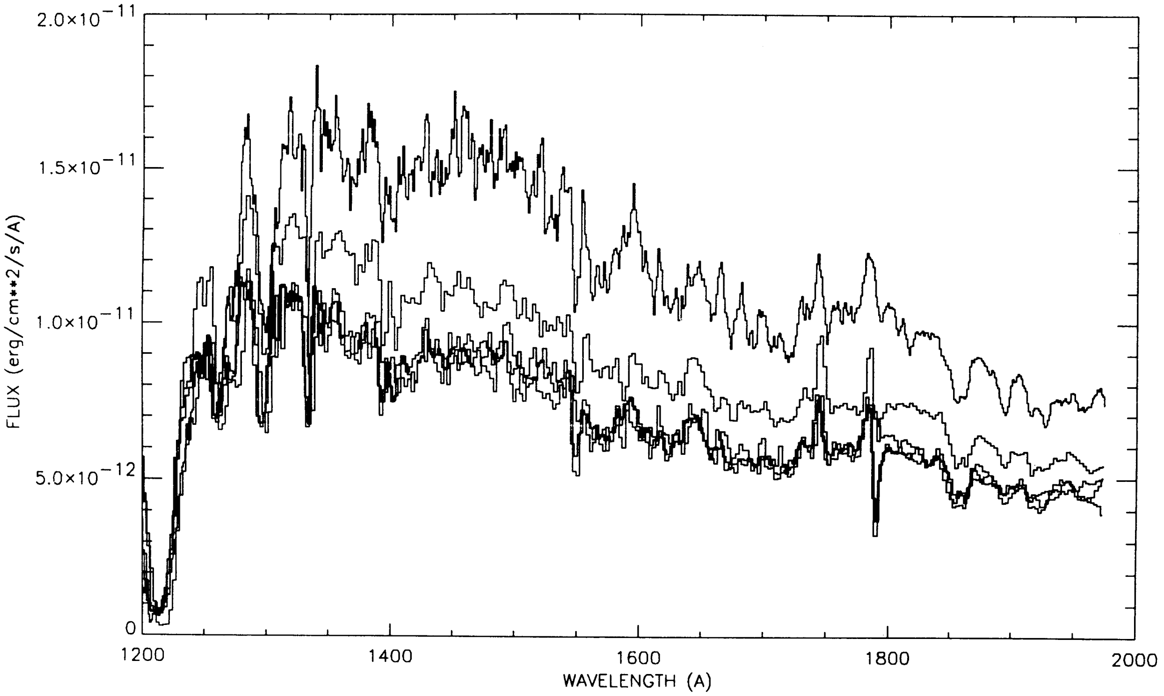

FIG. 2.—SWP spectra of HD 45677. The three low-flux states are from 1978 April 19 (SWP 1388), 1979 September 19 (SWP 6569), and 1980 February 21 (SWP 8006). The slightly higher spectrum is from 1978 September 26 (SWP 2772), indicating a small but significant change from 5 months earlier. The highest spectrum is from 1992 February 20 (SWP 44033), and is approximately 60% higher than the lowest fluxes shown.

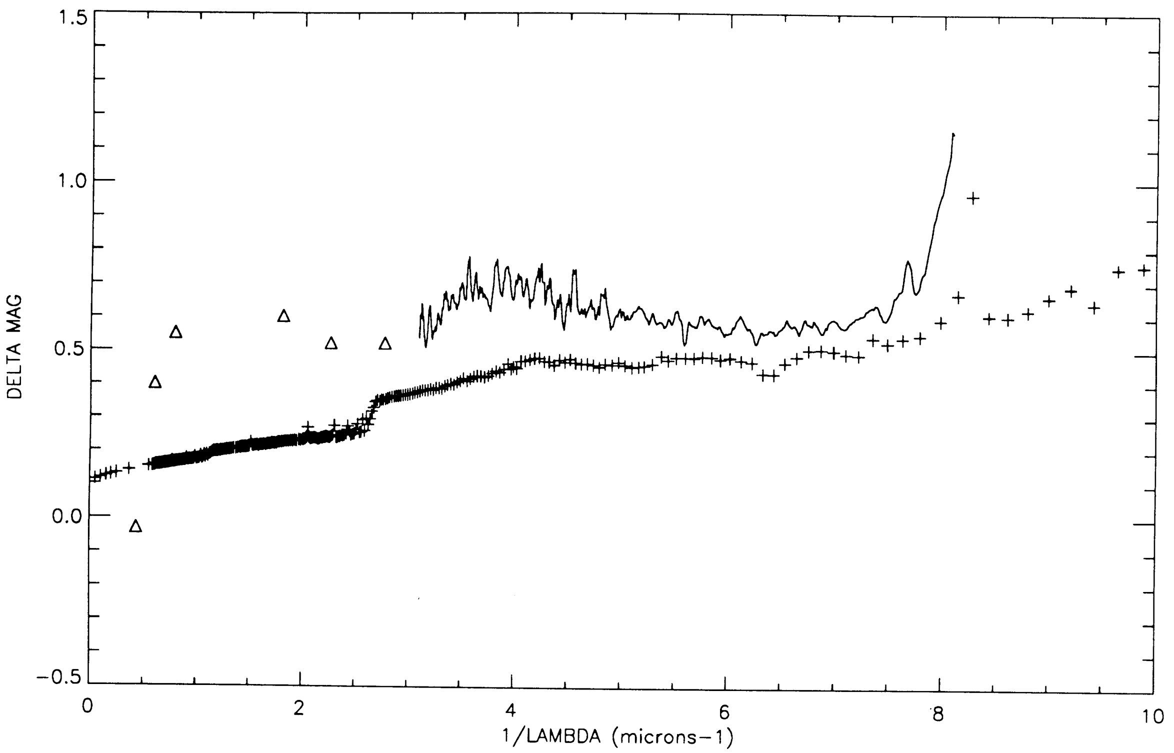

FIG. 3.—Difference in magnitude vs. wavelength in HD 45677 using *IUE* spectra (*solid line*) and *UBVJHK* data (*open triangles*) from 1980 and 1992. If interpreted as due to a change in circumstellar extinction, the extinction is nearly gray down to the longest wavelength not dominated by thermal emission. For comparison, the difference expected by a change in stellar surface temperature from 20,000 K to 22,500 K is shown (*plus signs*).

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inhomogeneous dust envelope can also produce gray extinction (Natta & Panagia 1984) as the cloud begins to behave more like a collection of optically thick occultors.

4.2. *IR Variability*

In Figure 4 we show the total flux (λF_λ in W m^{-2}) for the two epochs. Even a cursory visual inspection shows that the ratio of the two UV-optical spectra is nearly constant, as was shown in Figure 3. It would also appear that the IR flux measured in 1992 is systematically lower by about 30% than that of the earlier epoch. Since the dust envelope is optically thin in the IR, this can only occur if either the total heating rate is lower (however, the observed stellar flux actually *increased* during this time), or the total mass of the dust decreased (at least where it is close enough to the star to be heated and radiate in the near-IR). Since the thermal IR emission longward 3 μm is about 3 times that of the UV-optical emission, the total decrease ($\sim$30%) in IR emission is comparable to the increase ($\sim$60%) in the UV-optical emission.

4.3. *Dynamics of the Dust*

Possible explanations for the observed variability are that a cloud of material orbiting the star has moved out of the line of sight between the epochs, that some of the grains have recently spiraled in close to the star and have evaporated, or that the grains have been accelerated out of the nearby environment. These variations may or may not have a causal connection with the observed decline in IR emission. Below, we outline some of the possible scenarios.

4.3.1. *No Radial Transport: Cloud Orbital Motion*

The peak emission (in λF_λ W m^{-2}) occurs at $\lambda \sim 5$ μm, which corresponds to $T \sim 700$ K, while the coolest grains we could observe throughout this time interval emit at $\lambda \sim 20$ μm, or $T \sim 200$ K. For grains with blackbody emissivities and a stellar temperature of 22,000 K, these are located roughly 500 and 6000 stellar radii, respectively. These correspond to 12 and 140 AU. For a stellar mass of 10 $M_\odot$, grains in Keplerian or near-Keplerian orbits will have periods of 13 and 500 yr, respectively. A significant change in 3 yr is certainly possible in the inner regions if the dust is patchy, and might therefore be responsible for the shorter term changes seen in the UV and optical.

4.3.2. *Inward Transport: Grain Heating and Evaporation*

The near-equality of the increase in observed UV-optical flux and decrease in IR flux is what would be expected if the mass of dust responsible for the extinction had decreased. Grain loss can occur if the dust is transported close enough to the star that it evaporates.

For evaporation to be effective, a substantial fraction of the grains would have to be transported inward on rapid timescales. With evaporation temperatures for refractory grains of $T \sim 1500$ K, the grains would have to be transported to $\sim$2.5 AU in 3 yr if radiation is the main heating mechanism. The shortest possible timescale for inward transport will be the free-fall time. While the free-fall time for an object going from 12 to 2.5 AU is 2.2 yr, and this is just barely short enough to explain the changes seen, there is no obvious physical mechanism that will do this.

Poynting-Robertson drag will cause grains to spiral in on a timescale

$$t_{\rm P-R} = 7 \times 10^2 \, \frac{a_{\mu{\rm m}} \rho_g R_{\rm AU}^2}{Q_{\rm pr}(L_*/L_\odot)} \ {\rm yr} \qquad (1)$$

(Burns, Lamy, & Soter 1979), where $a_{\mu{\rm m}}$ is the radius of the

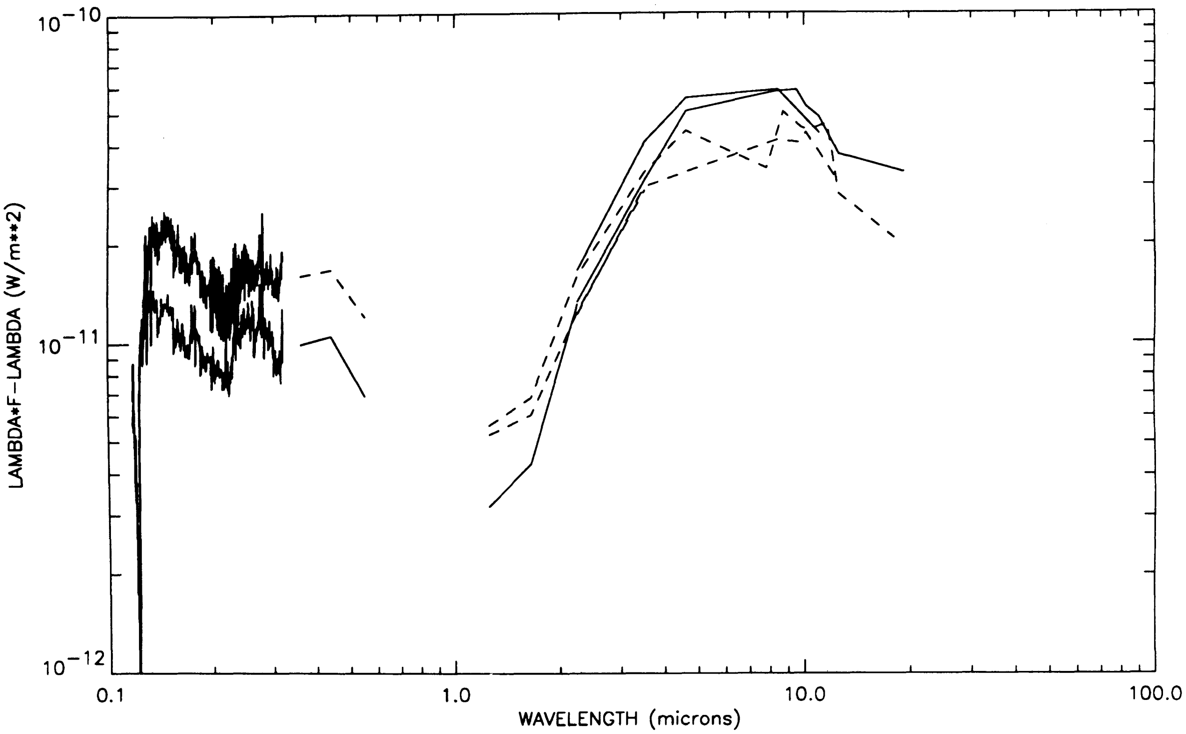

FIG. 4.—UV-to-IR flux of HD 45677 for 1980 and 1992. The 1980 data are indicated by the lower *IUE* spectrum and the solid lines, and the 1992 data by the upper *IUE* spectrum and the dashed lines. The wavelength-independent nature of the received stellar flux is apparent down to 1.65 μm (*H* band), with the star having brightened by $\sim$60% between 1980 and 1992. During the same time, however, the thermal emission seems to have declined by $\sim$30% (see Table 2).

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grains in μm, ρ_g is the cgs density of the grain material (assumed solid), R_{AU} is the distance of the grain from the star in AU, L_* is the luminosity of the star in solar units, and Q_{pr} is the dynamical efficiency of radiation pressure integrated over the star's spectrum. For grains larger than about 0.01 μm, this value is in excess of 0.2 and generally close to unity for a hot photospheric spectrum for both silicates and graphite (see Laor & Draine 1993, who discuss this problem for reddened and unreddened AGN spectra). For a B2 star near the main sequence, $L_* \sim 6 \times 10^3\ L_\odot$ and for $Q_{\text{pr}} \sim 1$, $\rho_g \sim 3$ g cm^{-3}, and $R_{\text{AU}} \sim 10$, the time for 2 μm grains to be lost is 70 yr. While this is only marginally effective over a decade for these grains, it is certainly effective over longer timescales.

4.3.3. *Outward Transport Acceleration by Radiation Pressure*

For a B2V star with $L/M \sim 600$ (in solar units), radiation pressure can drive all grains smaller than $\sim$40 μm (where $F_{\text{rad}}/F_{\text{grav}} \sim 2$) from $\sim$6 AU ($T \sim 1000$°K) to $\sim$600 AU ($T \sim 100$°K) in 50 yr, assuming no drag by circumstellar gas (see the Appendix).

It is easy to show that ejection of grains from the circumstellar environment is very efficient if the dust is not strongly coupled to the gas. Under this condition, the ratio of radiation pressure to gravitational pressure is

$$\frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{3L}{16\pi GMc} \frac{Q_{\text{pr}}}{a\rho_g} , \tag{2}$$

where M and L are, respectively, the mass and luminosity of the star and a and ρ_g are, respectively, the radius and bulk density of the grains in cgs units.

For a B2 star near the main sequence, $L \sim 6 \times 10^3\ L_\odot$ and $M \sim 10\ M_\odot$. For these parameters, radiation pressure exceeds the gravitational force when the radius of the grain is

$$a < 10^2 Q_{\text{pr}}\ \mu\text{m} . \tag{3}$$

So we would expect that all grains smaller than 10 μm and perhaps up to 100 μm may be gradually lost to the star, in agreement with the extinction results.

If, on the other hand, the dust is charged and strongly coupled to the (ionized) gas, so that it must drag the gas with it,

$$\frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{\sigma_{\text{pr}}}{\sigma_{\text{es}}} \frac{L}{L_{\text{Edd}}} , \tag{4}$$

where L_{Edd} is the Eddington luminosity, σ_{pr} is dust radiation opacity per H atom, and σ_{es} is the cross section per electron (Laor & Draine 1993). Under this condition, the ratio of radiation force to gravity approaches unity for a gas/dust mass ratio of 100 and 1 μm grains. Thus, radiation will be still be able to accelerate grains smaller than 1 μm. If the dust clouds are located in a torus, most of the grain loss will occur at the more exposed (and lower density) upper and lower surfaces. Within the gas/dust disk, the gas drag is much more important. The distance a grain travels before it has collided with a comparable mass of gas can be found by equating the grain mass with the mass of gas swept out by the grain

$$n\pi a^2 l m_p = \frac{4}{3} \pi a^3 \rho_g , \tag{5}$$

or

$$l = \frac{4a\rho_g}{3nm_p} \approx 5 \times 10^6 \frac{a_{\mu\text{m}} \rho_g}{n}\ \text{AU} , \tag{6}$$

where n is the number density of the gas in cm^{-3}, l is the path length traveled in cm, and ρ_g is the internal density of the grains in g cm^{-3}, a is the grain radius in cm, and $a_{\mu\text{m}}$ the radius in μm.

While the density of gas in the region occupied by dust is not known, it has been suggested that the dust is located somewhat beyond the inner edge of the forbidden-line region in Ae/Be stars in general (Berrilli et al. 1992) and for HD 45677 in particular (Swings 1973). As noted by SSM81, the detection of [N II] by Swings indicates that much of the gas must have $n < 10^5$. For $a \sim 1$ μm and $\rho_g \sim 3$ g cm^{-3}, $l \sim 150$ AU. In higher density regions, the "effective" mean free path is smaller.

It is beyond the scope of this paper to develop a detailed model of the disk around HD 45677, but we note than Berrilli et al. (1992) have modeled the IR emission in HAEBE stars using a dusty reprocessing disk with a radial gas density gradient

$$n(r) = n_0 \left(\frac{r_0}{r}\right)^\alpha , \tag{7}$$

with $n_0 \sim$ few $\times\ 10^8$ cm^{-3} and $r_0 \sim R_{\text{star}}$, and $\alpha \sim 0.5$. As a rough approximation, we note that for HD 45677, if $n_0 \sim 10^9$, $R_{\text{star}} \sim 5\ R_\odot$, and assuming a gas/dust mass ratio $\sim$100 and 1 μm grains with $\rho_g \sim 3$ g cm^{-3}, the integrated optical depth from 12 AU to 140 AU is $\sim$0.2, about what is expected based on the optical variations and implied optical depth.

4.6. *Summary*

We conclude that the longer term changes in the UV and IR light of HD 45677 are most likely due to the removal of grains (even modest-sized ones) due to radiative acceleration. The presence of a 9.7 μm silicate feature, however, suggests some grains smaller than a few microns are present. Many of these may be situated above and below the disk as they are driven outward and would contribute little to the observed line-of-sight extinction. Whether they are inside or outside the disk, since these grains will be lost to the system over the course of a few years, there must be a source of additional small grains. These could be partly replenished if grain-grain (boulder-boulder?) collisions are still occurring in the disk. A similar situation is observed for β Pic (Backman, Gillett, & Witteborn 1992). Knacke et al. (1993) have suggested that the dust torus surrounding β Pic may be due to the disruption of comets. The *IRAS* Low Resolution Spectrometer data (Olnon et al. 1986) for HD 45677 exhibits a silicate feature with a flattening between 9.4 and 10.9 μm which, when normalized to the continuum emission, is like those seen in comets (see Hanner et al. 1994), and a similar process could be operating HD 45677. If so, the circumstellar envelope around HD 45677 is still evolving. If the decrease in the IR emission over the past decade is real, it might be evidence of this evolution.

In this scenario, the shorter-term UV and optical flux variations are likely due to small fluctuations in the line-of-sight extinction due to the clumpiness of the dust distribution. The larger decade-long changes in UV and optical brightness might signal that a relatively clear hole has temporarily moved into the line of sight, perhaps coupled with a major loss of mass in small grains.

5. THE NATURE OF HD 45677

A number of years ago Swings (1973) suggested, based on the profiles of the emission lines, that the gas surrounding HD 45677 was located in an equatorial disk. A recent examination of high-resolution *IUE* spectra by Grady et al. (1993) found evidence for infall of material; that is, the star appeared to be accreting the gas from the equatorial disk. This strongly suggested that HD 45677 was a young object, and most likely a previously unrecognized HAEBE star.

The nature and location of the dust has been problematic. Swings & Allen (1971) envisioned the dust as being in a sphere roughly 32 AU in radius, and the star itself located at about 1 kpc from the solar neighborhood. Sitko (1981) found a rough energy balance between the UV deficiency and IR excess of the star which also indicated a spherical geometry. However, more recently the polarization of HD 45677 (Schulte-Ladbeck et al. 1992) provided very strong evidence for a planar or toroidal geometry for the dusty material surrounding the star. The two are difficult to reconcile unless either the energy-balance calculation of Sitko (1981) was incorrect or the dust disk is geometrically thick enough (nearly spherical) that approximate energy balance between the UV deficiency and the IR excess is observed.

It is now apparent that the energy balance determined by Sitko, *and probably any similar arguments in the literature for similar objects*, is faulty due to assumptions made about the optical properties of the dust. Sitko determined the UV deficiency by assuming the extinction of HD 45677 at 1 μm was negligible. This argument, while reasonably good for normal interstellar extinction and the colors of HD 45677, is simply wrong when substantial amounts of "gray" extinction are present. For HD 45677, about 0.6 mag of gray extinction was present in the 1980 data and not taken into account in the analysis. The use of a "normal" extinction law to deredden the spectral energy distributions of any star of this type, as has been done by Hillenbrand et al. (1992) and others in the past, must now be viewed with great skepticism.

How far away is HD 45677, and what are the contributions of the interstellar and circumstellar extinction? In Figure 5 we show the flux ratio of HD 45677 in its high (relatively unobscured) state compared to HD 42690, a B2V star originally used by SSM81 to derive the extinction curve for HD 45677. This ratio has been corrected for a difference in distance modulus of 2.4 mag. This difference is consistent with the distance of HD 42690 as 300 pc (normal for a $V = 5.0$, B2 V star) and HD 45677 being at a distance of 900 pc. Also shown is a normal extinction curve, using the parameterization of Cardelli, Clayton, & Mathis (1989) for $E(B-V) = 0.2$ mag. The agreement between the observations is now quite satisfactory down to $\lambda = 1300$ Å. Based on these data, we would conclude that the energy distribution of HD 45677 is consistent with a distance of 900 pc, foreground interstellar extinction due to normal interstellar dust with $E(B-V) = 0.2$ mag, and variable amounts of gray extinction, the last being close to zero in 1992. However, photometry of HD 45677 taken from the plate archives of the Harvard College Observatory by Swings & Swings (1972) indicate that the star was closer to $m_{\rm pg} \sim 7.0$ earlier this century. If this represents the true photospheric emission of HD 45677, it suggests that the star still suffers considerable circumstellar extinction and may have a higher intrinsic luminosity than that of a B2 V star. If HD 45677 is actually a B1 V or B2 III–IV (Burnichon et al. 1967 originally classified it as B2 IV), then its absolute visual magnitude would be 1 mag brighter (Lang 1992) and an additional magnitude of gray extinction may be present. The value of $E(B-V) = 0.2$ is also higher than indicated by observations with the Hopkins

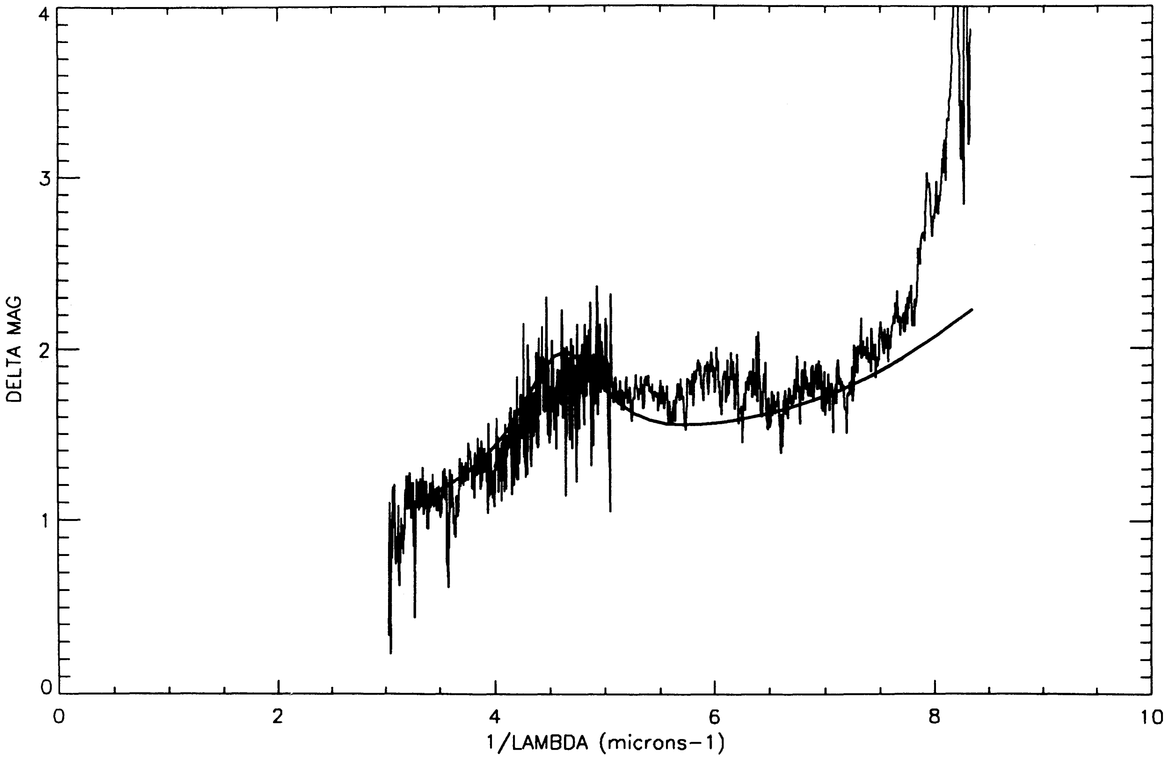

FIG. 5.—Difference in UV flux of HD 45677 and HD 42690, "moved" from a distance of 300 pc to 900 pc (a difference of 2.4 mag in apparent brightness). Superimposed is the extinction curve of Cardelli et al. (1989) for $E(B-V) = 0.2$ mag. The curve passes through the points least affected by line emission in HD 45677 at longer wavelengths and close to the point least affected by line absorption at shorter wavelengths. Residual Lα absorption may be present.

Ultraviolet Telescope (Brown et al. 1994), which require a flatter extinction curve in the far-UV. If so, the true extinction (at least at the time of those observations) would be more similar to that seen in some stars in Orion (Fitzpatrick & Massa 1988). Future observations of HD 45677 in a brighter state would be extremely valuable.

Maddalena et al. (1986) have mapped the region of the sky containing HD 45677 in the emission lines of CO. HD 45677 lies ~3° south of a molecular complex that stretches from the Mon R2 cloud to the CMa OB1 complex. They derive a distance to the region nearest the projected position of HD 45677 as being 900 pc, the same as we derive for the star itself. At this distance, HD 45677 has a projected *and true* distance of about 60 pc from this cloud.

HD 45677 probably is a star located near a molecular cloud complex and contains a circumstellar disk of processed dust and gas, from which it is accreting material. It has all the characteristics of what an aged HAEBE star should be like.

6. CONCLUSIONS

We looked for and detected long-term changes in the UV-optical light of HD 45677. We found that if the variations are due to changes in the circumstellar dust extinction, the extinction of the circumstellar grains is very gray. The circumstellar envelope surrounding HD 45677 is probably deficient in grains smaller than 1 μm, compared to the general interstellar medium. This is to be expected as radiation pressure from the star should be effective at removing grains smaller than 10 μm. The decline in IR emission during the same time span is consistent with the star's ability to remove grains episodically by radiation pressure. But the persistence of small grains, as indicated by the 9.7 μm silicate feature, would require a mechanism for replenishment. The disruption of larger bodies, such as comets, might help replenish the smaller (1 μm) particle population. If this idea is correct, then we would expect that future changes in UV flux would be accompanied by similar changes in the IR, and these would be opposite in sign from one another. We would also expect that the silicate feature would look similar to that of comets (Hanner et al. 1993) and possibly of β Pic (Knacke et al. 1993), as seems to be the case (Sitko et al. 1994).

We have found that the spectral energy distribution of HD 45677 is consistent with a distance of about 900 pc, nearly normal interstellar extinction with $E(B-V) = 0.2$ mag, and variable gray extinction. The star appears to be in close association with the molecular cloud complex between Mon R2 and CMa OB1 and is most likely a HAEBE star in an advanced evolutionary state. We note that Grinin et al. (1991) have observed photometric and polarimetric variations in HAEBE stars and found that they are correlated, and that a disk geometry like that in HD 45677 was implicated. While such detailed correlated photometric/polarimetric observations of HD 45677 are not yet available, the star should show similar behavior.

We also caution all investigators that using "normal" interstellar extinction curves to deredden spectral energy distributions of stars surrounded by dusty envelopes may lead to significant errors in the interpretation of their data.

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APPENDIX

While the free-fall timescale for grain trajectories accelerated by radiation pressure is sometimes assumed (see Backman & Paresce 1992), this is incorrect, especially for accelerations for distances over which the radiative force changes appreciably. While an exact expression for the free-fall trajectories is sometimes derived in textbooks on mechanics, the latter is rarely seen.

The time for an object to fall radially in a gravitational field from an initial distance $r_{\rm in}$ to a smaller distance r is

$$t = \sqrt{\frac{r_{\rm in}}{2GM}} \left(r_{\rm in} \arccos \sqrt{\frac{r}{r_{\rm in}}} + \sqrt{r r_{\rm in} - r^2} \right) . \tag{A1}$$

However, it can be shown that an accelerating force acting to push the same mass from $r_{\rm in}$ to r requires an interval of time given by

$$t = \frac{r_{\rm in}^{3/2}}{[2(\beta - 1)GM]^{1/2}} \left\{ \sqrt{\left(\frac{r}{r_{\rm in}}\right)^2 - \left(\frac{r}{r_{\rm in}}\right)} + \ln\left[\tan\left(\frac{\pi}{4} + \frac{1}{2} \arccos \sqrt{\frac{r_{\rm in}}{r}} \right) \right] \right\} , \tag{A2}$$

where

$$\beta = \frac{F_{\rm rad}}{F_{\rm grav}} \tag{A3}$$

is the ratio of the force of radiation pressure to that of gravity.

That these cannot be the same is seen by simply realizing that for free-fall, most of the time is spent where F is small, while for outward acceleration, most of the time is spent where F is large, resulting in a larger velocity change.

$$m\,dv = F\,dt . \tag{A4}$$

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