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THE GROWTH OF SOLIDS, DESTRUCTION OF MOLECULES, AND SHIELDING OF RADIATION IN THE YOUNG STELLAR DISK OF HD 45677

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ABSTRACT

Ultraviolet spectra (912–3300 Å) from the Astro-1 and *IUE* space missions of two Herbig Be stars, HD 45677 and HD 200775, show that the HD 200775 intrinsic continuum shape generally coincides with a $T = 20{,}000$ K Kurucz model and that the HD 45677 continuum exhibits additional line blanketing, extinction, and emission from gas and dust in its disk and bipolar wind. With $\log N(\text{H I}) = 21.4 \pm 0.1$ cm^{-1}, our measured upper limit on the fraction of HD 45677 disk H atoms in molecules ($f < 1.5 \times 10^{-2}$) is much less than that seen in general Galactic molecular clouds ($f \approx 0.5$). Also, our derived HD 45677 circumstellar dust extinction for $\lambda > 1400$ Å is produced by an inhomogeneous disk of material: during periods of moderate visual extinction ($A_V \approx 1.0 \pm 0.3$ mag) the disk as a whole causes mid-UV extinction with an $R_V \approx 4$–5 (values found in Galactic molecular clouds), yet at the thickest optical depths, there are regions with larger grains (inferred $R_V > 7$) than those in molecular clouds ($R_V < 5.6$).

Alternately, we find in the FUV (1300–1000 Å) a strong, steeply curved circumstellar extinction for HD 45677 that has a very similar shape as extinction produced by interstellar polycyclic aromatic hydrocarbon molecules (PAHs) in an illuminated molecular cloud (NGC 2023). The PAHs around HD 45677, like NGC 2023, are more abundant relative to the large grains (A_λ/A_V) than predicted by the extinction parameter R_V, because HD 45677 has evaporated the PAHs off large grains. With a measured FUV depth corresponding to $\tau_\lambda \approx 1.4$–3.5, the excess PAHs around HD 45677 partly shield the outer disk from FUV radiation.

Both the disk gas and dust have evolved greatly since the formation of the midmass star HD 45677 from molecular clouds: in some regions, the disk grains have grown to micron sizes suitable for the formation of planetesimals, the ISM H_2 has been photodissociated into H I in the disk, and CO (McGregor, Hyland, & Hillier 1988) has disappeared. In addition, the molecular PAHs that are condensed onto grains in molecular clouds have photoevaporated off grains into the gaseous disk of HD 45677, becoming dehydrogenated and ionized. Thus, because of strong FUV radiation from HD 45677 and moderate FUV shielding, the disk around this intermediate-mass star differs dramatically from the condensate-rich, molecular gas around low-mass stars and would seem to lead to a different chemical and physical evolution toward planets than those around low-mass stars such as our Sun.

Subject headings: circumstellar matter — dust, extinction — stars: emission-line, Be — ultraviolet: stars — stars: individual (HD 45677)

1. INTRODUCTION

Herbig Be stars (Thé, de Winter, & Pérez 1993; Herbig 1959) are a class of intermediate-mass pre–main-sequence stars that share many spectroscopic properties with the low-mass T Tauri stars. In particular, both types show infrared (IR) and visual emission from circumstellar gas and dust that apparently has formed from molecular clouds. In this paper we examine the gas and dust around the B2 IVe star HD 45677 (Burnichon et al. 1967) to look for evolution of the disk gas and dust as compared to those of molecular clouds in the interstellar medium (ISM) and around low-mass stars.

Located at $\alpha = 6^h25^m59^s$ and $\delta \doteq -13°01'12''$ (SAO, 1950), HD 45677 is seen edge-on through its disk, as indicated by a rapid $v \sin i \approx 200$ km s^{-1} stellar rotation (Swings & Allen 1971) and a photometric variability of $9.58 \geq V \geq 7.55$ mag (Mendoza 1958; Feinstein et al. 1976; Halbedel 1989, 1992) from variable obscuration. UV polarimetric observations of HD 45677 (Schulte-Ladbeck et al. 1992) found polarization from a bipolar reflection nebula perpendicular to an edge-on disk. Using high-dispersion *IUE* spectra from 1979 to 1992, Grady et al. (1993) detected high-velocity accreting gas toward HD 45677. All the evidence, including detection of scattered light at minimum (Pérez et al. 1994), indicates that HD 45677 is a Herbig Be star with an actively accreting circumstellar, possible protoplanetary, disk that fully occults the star. However, unlike many intermediate-mass (Herbig Be) young stars, HD 45677 sits clear of molecular nebulosity.

Another similar temperature (B2.5–3 Ve) Herbig Be star, HD 200775 (Buss et al. 1994; Whitcomb et al. 1981 and references therein), is located at $\alpha = 21^h00^m59^s$ and $\delta = +67°57'56''$ (SAO, 1950). However, HD 200775 illuminates the reflection nebula NGC 7023 and lies with its pole tilted toward our sight line: the measured $v \sin i$ is approximately 60 km s^{-1} (Hillenbrand et al. 1992), and the flux is virtually nonvariable in the visual ($V = 7.38$ mag; Pfau, Piirola, & Reimann 1987), even though there is moderate IR excess from the disk. The sight line does not pass through the disk, and we use HD 200775, after correcting for the HD 200775 nebular extinction, as a comparison star to model the photosphere of HD 45677.

In this paper, we determine the $\lambda = 1000$–1700 Å dust extinction through the HD 45677 disk, at an optically thin $A_V \approx 1.0 \pm 0.3$ mag, by comparing the edge-on HD 45677 to the more face-on HD 200775. In contrast, Sitko, Savage, & Meade (1981) paired a normal, main-sequence B2 V star spectrum to that of HD 45677 (at $A_V[\text{disk}] \geq 0.5$ mag), and found a nearly flat extinction for $\lambda > 1300$ Å (7.8 μm^{-1}). The intrinsic spectrum of the HD 45677 pre–main-sequence star, however, might differ from that of a main-sequence star, so the HD 45677–HD 200775 pair provides an improved measurement of the visually optically thin circumstellar dust. In particular, how flat is the extinction throughout the UV, and how much does the disk extinction increase below 1300 Å, where strong absorption and extinction from H I and small dust can occur?

By intercomparing spectra of HD 45677 itself between the dim $V = 8.04$ mag and extremely faint ($V = 8.64$ mag) phases during 1992 and 1980, Sitko et al. (1994) found that large ($a \geq 1$ μm) grains cause nearly flat (gray) circumstellar extinction from 1300 Å to 1.6 μm for regions of the HD 45677 disk that increase the visual extinction from $A_V \geq 0.5$ to ≥ 1.1 mag. These grains are composed partly of silicates (9.7 μm emission; Olnon & Raimond 1986) and are large, like the nascent grains around cool supergiants (Snow et al. 1986). However, does the extinction through the *entire* thin part of the HD 45677 disk, during a period of moderate extinction ($A_V \approx 1.0 \pm 0.3$ mag), differ from the extinction in the regions sampled by Sitko et al. (1994)? Is there small dust in the HD 45677 disk, and if so, what is its composition? How much has the dust and gas evolved in the HD 45677 disk, and has the star itself played a role in the evolution?

To address these questions, we have obtained simultaneous Hopkins Ultraviolet Telescope (HUT) and Wisconsin Ultraviolet Photo Polarimeter Experiment (WUPPE) spectra of HD 45677, as well as HUT and *IUE* spectra of HD 200775. The observations extend the spectral coverage below 1300 Å to the Lyman limit at 912 Å, providing a sensitive measure of the relative proportion of small dust, as well as a good measure of the resonance H I and H_2 absorptions in the FUV. We thus investigate the size, composition, and abundance of the grains and gas in the HD 45677 disk to look for its evolution with respect to molecular clouds from which it was born.

2. OBSERVATIONS

Because of its variability, we observed HD 45677 simultaneously with the Astro-1 HUT and WUPPE spectrometers, as well as with the *IUE Observatory* fine error sensor (FES). The HUT spectrum and *IUE* spectrum of the nonvariable HD 200775 were taken about a decade apart.

2.1. *Hopkins Ultraviolet Telescope*

HUT observed HD 45677 and HD 200775 on 1990 December 5 at 2:02 GMT and on 1990 December 9 at 10:51 GMT, respectively, during the Astro-1 mission aboard the Space Shuttle Columbia. HUT uses a 90 cm diameter $f/2$ primary mirror and a prime focus, near-normal-incidence, Rowland-circle grating spectrograph to obtain ~3 Å resolution spectrophotometry through an 18″ aperture in the far-ultraviolet (FUV) band from 830 to 1860 Å in first order. The detector consists of a microchannel plate coupled to a phosphor intensifier that is read by a Reticon into 2048 pixels. A complete description of the instrument and its calibration is given in Davidsen et al. (1992).

HD 45677 was observed for 1846 s from terrestrial night into day, while HD 200775 was observed for 2028 s from day into night, resulting in airglow contamination lines from Lyα at 1216 Å and O I at 1304 Å. Figure 1 shows the flux-calibrated spectra of the two objects as observed during the mission. Besides corrections for dark counts, spectrograph second-order counts (present for $\lambda > 1824$ Å), and scattered-light contamination (measured at $\lambda < 912$ Å), we statistically analyzed at 2 s intervals the count rates in regions free of airglow lines in order to correct for unstable pointing, assuming Poisson arrival rates of photons and using the Kolmogorov-Smirnov test. Thus, we multiplied the raw HD 45677 fluxes by a factor of 1.20 ± 0.02, and those of HD 200775 by 1.25 ± 0.02, to obtain absolute fluxes corrected for light loss due to pointing jitter.

2.2. *International Ultraviolet Explorer*

The *IUE* spacecraft, science instrument, and data handling are described in Boggess et al. (1978) and in Harris & Sonneborn (1987). Reduction of the *IUE* data and use of the FES to estimate the V(FES) is given in Pérez, Grady, & Thé (1993).

The *IUE* FES measurement of HD 45677 was made on 1990 December 5 at 5:29:00 GMT, some 3 hr following the start of the Astro-1 observations, and yielded an equivalent $V(\text{FES}) = 8.25$ mag. V(FES) was calculated assuming no $B-V$ color correction, since there is no strictly simultaneous photometry.

The HD 200775 observations, using the long wavelength redundant (LWR) camera spectrometer, were made on 1979 July 27 and consist of small (SMAP) and large aperture (LGAP) spectra. In LWR 5178, the 2450–3000 Å region in the SMAP spectrum is overexposed, so we spliced the LGAP and SMAP data at 2450 Å, scaling the better S/N SMAP data shortward of this point by a factor of 2.0 to match the LGAP level. We then corrected the combined spectrum to the new *IUE* calibration (Linsky & Bohlin 1993), which is within a few percent of the HUT flux calibration. The fluxes of the *IUE* LWR spectrum and HUT spectrum match closely at 1860 Å (Fig. 2).

2.3. *Wisconsin Ultraviolet Polarimeter Experiment*

Schulte-Ladback et al. (1992) describe the WUPPE spectrum of HD 45677. WUPPE was flux-calibrated to the old *IUE* calibration, so we corrected the WUPPE data to the new *IUE* calibration (Linsky & Bohlin 1993). The WUPPE flux had losses from unstable photometry, so we normalized it to the HUT flux in the wavelength overlap by a multiplication factor of 1.4.

3. ANALYSIS

We detect the HD 45677 flux down to 938 Å, where line blanketing from the H I Lyman series obliterates the stellar continuum (Fig. 1). Additional strong absorption from photospheric Lyβ 1025.7 Å is also present. Interstellar absorption toward HD 200775 eliminates flux below 1000 Å, except at the 989 Å terrestrial O I airglow line (Fig. 1). The depth of the Al II 1723 Å and Fe III 1891 Å absorptions in HD 45677 (Figs. 1, 2),

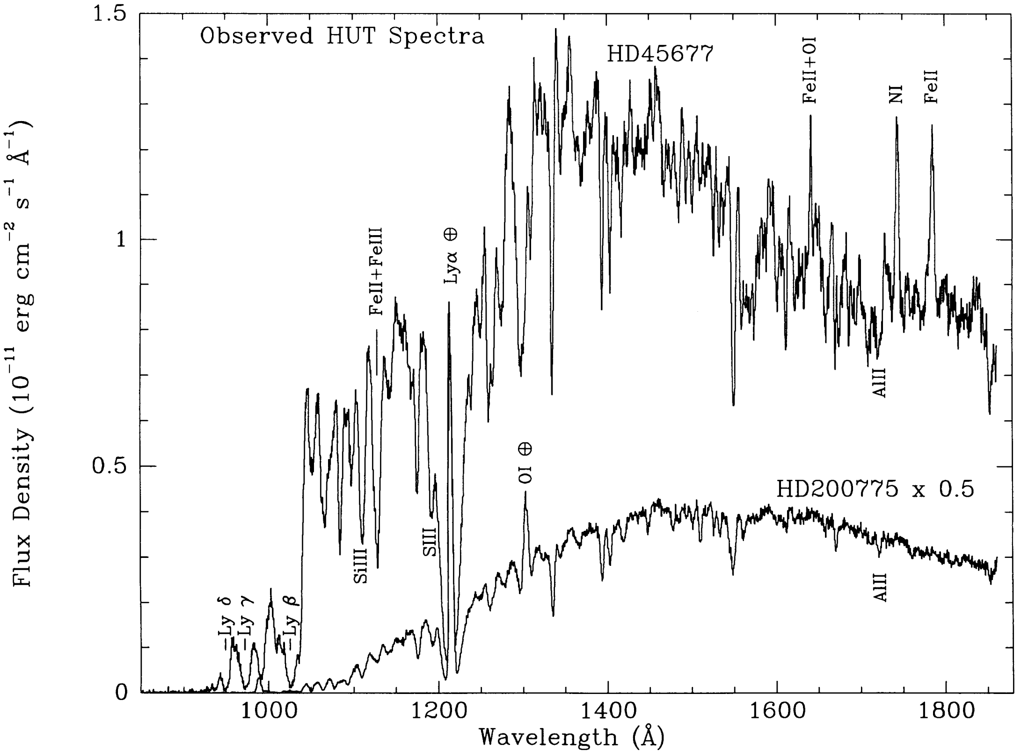

FIG. 1.—The observed calibrated HUT spectra of HD 45677 and HD 200775. Continuum extinction by dust greatly reduces the 912–1300 Å flux in both stars. The H I Lyman series is clearly present in HD 45677, but Lyα and O I terrestrial airglow emission contaminated both spectra. We label strong circumstellar emission and absorption lines in HD 45677 that are not in HD 200775. The other unlabeled absorptions above 1250 Å correspond well between HD 45677 and HD 200775.

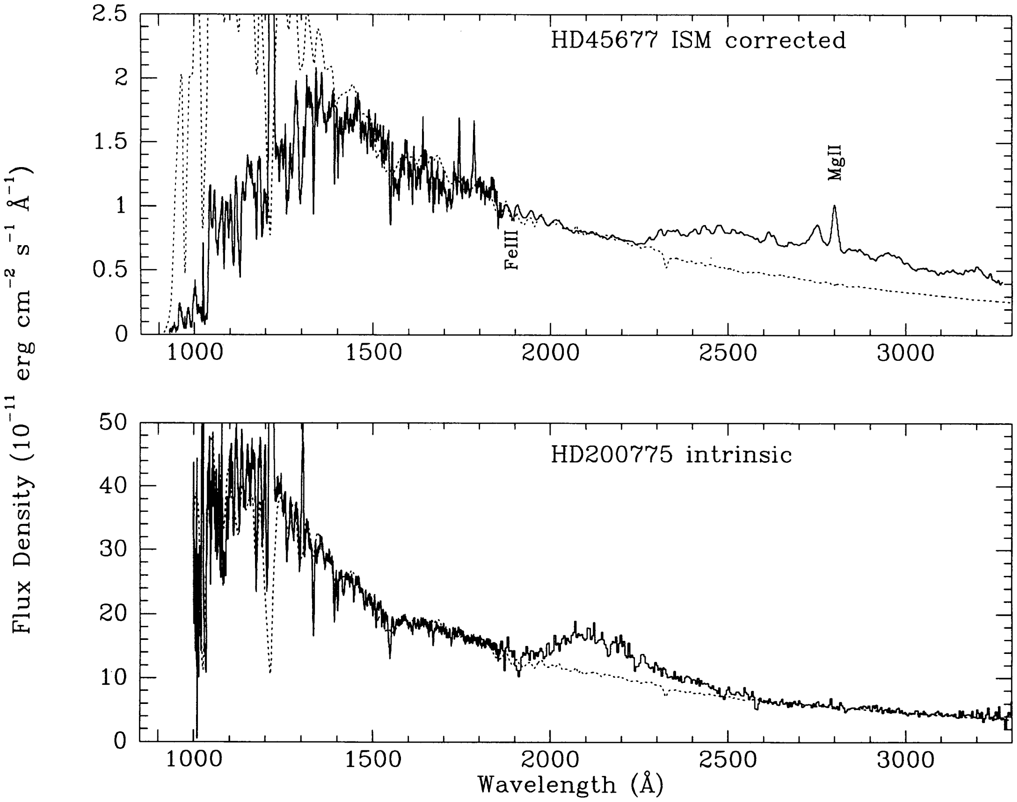

FIG. 2.—The ISM-corrected spectra of HD 45677, from a splice of the HUT and WUPPE spectra, and HD 200775, from a splice of the HUT and *IUE* spectra (*solid*). Continuum-normalized Kurucz models (T = 20,000 K, log g = 4; *dashed*) delineate photospheric continua in both stars. HD 45677 disk absorption (912–1400 Å) and circumstellar emission (2300–3250 Å) deviate from the model; the HD 200775 broad 2175 Å excess illustrates extinction-correction errors in this limited region.

when compred to MK standards (Heck et al. 1984; cf. Burnichon 1967), give it the appearance of a subgiant (IV), while those in HD 200775 are weaker, like those of a dwarf (V). The HD 45677 luminosity class IV might be due to the convolution of the photospheric absorption with that of the circumstellar gas, so the actual luminosity class of HD 45677 could be V.

3.1. *Interstellar Medium*

The total sight line toward HD 45677 passes through both the Galactic interstellar medium and the circumstellar disk. We demonstrate that the Galactic contribution is small, but we correct for it to obtain intrinsic HD 45677 spectrum.

Sitko et al. (1994) argue for a large $E(B-V) = 0.2$ mag, from interstellar, not circumstellar, extinction, based upon uncertain distance estimates to HD 45677, an extinction curve contaminated with emission, and on a false 2175 Å extinction strength. However, Savage et al. (1978) present a strong argument for a much smaller $E(B-V) = 0.0$–0.8 mag, with a nominal $E(B-V) = 0.04$ mag (cf. McGregor, Hyland, & Hillier 1988). Also, the plethora of partially resolved Fe II emission from 2300 to 3000 Å (Sitko & Savage 1980; Sitko et al. 1981), and the additional emission from 1750 to 1850 Å (Figs. 1, 2), give the false appearance of a dip in the flux at 2175 Å. Thus dereddening HD 45677 with $E(B-V) = 0.2$ mag incorrectly removes the ISM extinction by overestimating the fluxes at 2175 Å (cf. HD 200775, Fig. 2) and at all other wavelengths.

Using instead $E(B-V) = 0.04$ mag, the extinction (A_λ/A_V) of Cardelli, Clayton, & Mathis (1989, hereafter CCM), $R_V = A_V/E(B-V) = 3.1$ for the diffuse medium, and $A_V(\text{ISM}) = 0.12$ mag, we correct the ISM UV extinction toward HD 45677 (Fig. 1) to obtain the stellar and circumstellar flux (Fig. 2). A temperature $T = 20{,}000$ K, log (surface gravity) $\equiv \log g = 4.0$ Kurucz (1979) stellar (B2 V) atmospheric model at ~ 10 Å resolution, normalized to HD 45677 at 2000–2200 Å, illustrates that the 1400–2250 Å flux (Fig. 2) is mostly photospheric, while disk emission is significant at $\lambda > 2250$ Å. Since the HD 45677 circumstellar extinction is gray (see § 3.3 and Sitko et al. 1994) where we normalized the Kurucz model, the comparison to an unreddened Kurucz model is justified and shows additional disk absorption below 1400 Å. This absorption could mask any intrinsic photospheric or inner disk flux excess above the Kurucz model at $\lambda < 1400$ Å, though main-sequence Kurucz models seem to fit well the Herbig Be star HD 200775 in the UV, except from 1120–1180 Å (Fig. 2; see below).

We removed the FUV interstellar extinction (Buss et al. 1994) from the observed HD 200775 spectrum (Fig. 1) to obtain the "intrinsic" stellar spectrum (Fig. 2) below 1700 Å and above 2400 Å. All ISM H_2 and H I absorptions were removed, as well as photospheric Lyα from about 1150 to 1300 Å (Buss et al. 1994). The ISM 2175 Å extinction bump is weaker toward HD 200775 (Walker et al. 1980) than the Galactic average (CCM). To illustrate this, we show the HD 200775 flux, corrected by the mean bump extinction curve for a two-component $R_V = 3.0 + 3.55$ mean extinction formulation (Buss et al. 1994). A $T = 20{,}000$ K, $\log g = 4.0$ Kurucz (1979) model, normalized to the HD 200775 flux at 2500–3000 Å, deviates at the broad 2175 Å bump and at the sharp HUT 3 Å resolution absorption lines. Otherwise, the model matches well the intrinsic spectrum (Fig. 2), showing that the UV fluxes outside the bump are mainly photospheric except for an excess emission ($\sim 14\%$) between 1120 and 1180 Å, possibly due to the HD 200775 inner disk, or stellar photosphere, or overcorrected extinction. From 1000 to 1120 Å, the H_2 correction (Buss et al. 1994) restores the continuum to the approximate level of the Kurucz model, but an FUV excess might also be present here if the H_2 correction were underestimated.

3.2. *Hydrogen Absorption*

Using the atomic constants of H I (Allen 1981) to calculate Voigt profiles of the Lyman series, we measure the H I density through the HD 45677 disk [$\log N(\text{H I}) = 21.4 \pm 0.1$ cm^{-2}] from the observed Lorentzian damping wings of the $\lambda_0 = 1216$ Å Lyα line (Fig. 1). After minor corrections for ISM and photospheric H I (see below), this column restores the flux peaks in the 1140–1300 Å continuum (Fig. 2) to about the same sloping level, with some line blanketing from other atoms (e.g., S III, multiplet 1, λ1200 Å). If line blanketing is ignored, we find at most $\log N(\text{H I}) = 21.5 \pm 0.1$ cm^{-2} for the disk hydrogen. A model with an assumed disk gas Doppler microturbulent velocity $b = 3$ km s^{-1} and $T \approx 500$ K at $\log N(\text{H I}) = 21.4 \pm 0.1$ cm^{-2} removes both the Lyα wings and raises the core of Lyβ 1025.7 Å to the surrounding continuum level (Fig. 2). The model correction leaves photospheric pressure-broadened absorption wings at Lyβ (Fig. 2) and an excess emission in the 1216 Å Lyα core due to terrestrial airglow.

If the Bohlin, Savage, & Drake (1978) $N(\text{H I})/E(B-V)$ relation held for $E(B-V) < 0.08$ [$N(\text{H I})$ is likely to be lower because of ionization by UV photons in the ambient interstellar field (Diplas & Savage 1994)], the ISM reddening $E(B-V) = 0.04$ mag might correspond to an interstellar $\log N(\text{H I} + 2\text{H}_2) \approx 20.37$ cm^{-2} toward HD 45677. Using instead $\log N(\text{H I}) = 20.3$ cm^{-2}, and assuming $b = 15$ km s^{-1} and $T = 80$ K, we removed the ISM H I absorption for the HD 45677 spectrum before measuring the disk absorption. In addition, we crudely removed the small expected photospheric Lyα absorption ($W_\lambda \approx 10$ Å for a fully formed B2 star; Savage & Panek 1974). The gas kinetic model, ignoring stellar atmospheric effects, gave a $W_\lambda \approx 10$ Å for $\log N \approx 20.3$ cm^{-2}, assuming a $T = 22{,}000$ K gas with $b_{\text{rot}} = 90$ km s^{-1}, as might be found in a $v \sin i = 200$ km s^{-1} B2 IVe star. Alternatively, a hot disk might produce the photosphere, causing us to underestimate the disk $N(\text{H I})$, but in any case, *the stellar and interstellar components are at least 10 times smaller than the circumstellar* H I *component*. Ionized disk hydrogen does not seem important due to the lack of detectable radio emission (Woodsworth & Hughes 1977; Altenhoff et al. 1976).

By varying the column density $N(\text{H}_2)$ in a molecular hydrogen absorption model (see Buss et al. 1994; Morton & Dinerstein 1974), we constrained $\log N(\text{H}_2) \leq 19.3$ cm^{-2} in the HD 45677 disk, assuming $T = 200$ K (cf. Sorrell 1989) and a nonthermal $b = 3$ km s^{-1} in the H_2 gas. (A higher T lowers the upper bound.) We divided the transmissions of the models into the observed spectrum and examined the resultant flux at the strong H_2 bands, such as 1077 Å, that were almost unblended with absorptions from other species. The $\log N(\text{H}_2) \leq 19.3$ cm^{-2} upper limit was reached when the corrected flux at each strong band, considered separately, no longer exhibited excursions above the surrounding HD 45677 continuum and when HD 45677 still resembled the intrinsic HD 200775 spectrum from 1050 to 1110 Å. Considering at least five strong H_2 bands together, the limit would be $\log N(\text{H}_2) \leq 19.0$ cm^{-2} for HD 45677.

3.3. *HD 45677 Disk Extinction*

We now derive upper and lower limits to the HD 45677 disk extinction, A_λ/A_V, by pairing the ISM–corrected flux of HD 45677 to that of HD 200775, which has virtually the same spectral type and temperature (Fig. 2). Because we have overcorrected the ISM bump in HD 200775, it may be possible to fit a slightly cooler temperature to HD 200775 in the near-to-mid UV. If HD 45677 is 2000 K hotter than HD 200775, then this mismatch would *increase* A_λ/A_V by 0.3 in the vicinity of 9 μm^{-1}, with a smaller increase at longer wavelengths (becoming negligible at 7 μm^{-1}). For pairing, we use only fluxes for $\lambda < 1700$ Å (Fig. 2), discarding the emission-contaminated fluxes for $\lambda > 1700$ Å (HD 45677), and discarding the uncertain fluxes near the 2175 Å bump (HD 200775). We use the observed extinction (Walker et al. 1980), corrected by Buss et al. (1994), to deredden the HD 200775 spectrum, extrapolating shortward of 1330 Å with the two-component $R_V = 3.0 + 3.55$ mean extinction formulation (Buss et al. 1994). We also remove the contaminated regions of Lyβ, Lyα, O I, Fe II + O I, N I, and Fe II (Figs. 1 and 2). The disk extinction is given by

$$A_\lambda/A_V = 2.5 \log (c f_{\rm HD\,200775}/f_{\rm HD\,45677})/A_V ,$$

where $c = 0.25$ and 0.45 are flux scale factors corresponding to values of $A_V = 0.7$ and 1.33 mag for HD 45677. We estimate the disk $A_V \geq 0.7$ mag at the time of the HUT observation by subtracting the observed *IUE* FES $V = 8.25$ mag and the maximum historical $V = 7.55$ mag (Mendoza 1958). The large UV and optical variability of HD 45677 is due to variable disk extinction (Sitko et al. 1994), particularly since observations of near–pole-on Herbig Be stars show a small intrinsic variability on the order of 0.1 mag (Bibo & Thé 1993) due to circumstellar gas emission. Also, at $V = 8.25$ mag, our measured $\log N(\mathrm{H}) = 21.4$ cm^{-2} constrains $A_V \leq 1.33$ mag because the relation $A_V/N(\mathrm{H}) = 5.3 \times 10^{-22}$ mag cm^2 in the diffuse medium (Bohlin et al. 1978) is a maximum (cf. Diplas & Savage 1994; CCM 1989), although we note that this relation might increase if the dust-to-gas ratio has increased in the HD 45677 disk. The HD 45677 $V = 8.25$ mag and HD 200775 $V = 7.38$ mag during the HUT observations become $V_0 = 8.13$ mag and $V_0 = 5.93$ mag, respectively, after correction for A_V(ISM) = 0.12 mag for HD 45677 (see § 3.1) and A_V(ISM) = 1.45 mag for HD 200775 (Buss et al. 1994). Thus, we determined the scale factors c by normalizing the intrinsic visual magnitude of HD 200775 so that the V_0 magnitude would be 0.7 mag and 1.33 mag brighter than that of HD 45677, consistent with the inferred A_V.

The two extremes of HD 45677 disk extinction appear in Figure 3 (*solid, noisy*), along with empirical interstellar extinctions (*dashed*, CCM) that we judged to fit best from 6–8 μm^{-1}. The extinction through the *entire* thin part of the HD 45677 disk, during a period of moderate extinction ($A_V \approx 1.0 \pm 0.3$ mag), implies an R_V of 4–5, and results from a population of both large and smaller grains. We also compare our HD 45677 extinction with that of Sitko et al. (1994; Fig. 3, *crosses*). Neither of the two extremes of possible disk extinction (Fig. 3; *solid, noisy*) agrees with that derived by Sitko et al., but one should not expect agreement, because of different physical conditions in his and our sample. Sitko et al. compared the spectra of HD 45677 in times of moderate ($A_V \geq 0.5$ mag) and optically thick ($A_V \geq 1.1$ mag) extinction, and thus derived the extinction in the thick region of the HD 45677 disk corresponding to a visual extinction change from $A_V \geq 0.5$ mag to ≥ 1.1 mag. Our own FUV extinction curve probes the dust through the disk inner edge at $A_V \approx 0$ mag up to $A_V \approx 1.0 \pm 0.3$ mag. If fitted with the CCM ISM extinction, the extinction curve of Sitko et al. implies an $R_V > 7$, since the Sitko et al. extinction is extremely flat from the IR through the FUV (and results from a population of large grains).

Although our own observation implies an $R_V \approx 4$–5, within our derived limits on A_V, *our observed HD 45677 disk extinction cannot be fitted at all wavelengths by the empirical extinction of CCM with any value of R_V (Fig. 3) but instead deviates strongly upward in the FUV*. Such deviations from the general mean Galactic extinction of CCM occur in ISM bright nebulae (Mathis & Cardelli 1992) where the exciting star has increased the gaseous abundance of polycyclic aromatic hydrocarbon (PAH) dust by photoevaporating it off grains (Buss et al. 1994). In such nebulae, changes in 12 μm emission from tiny dust correlates with the FUV extinction deviation (Buss et al. 1994), and in particular, the 12 μm emission from NGC 2023 is from PAHs and their emission bands from 5 to 15 μm (Ryter, Puget, & Pérault 1987; Siebenmorgen & Krügel 1992). The identification of PAHs with these bands and the 3.3 μm band (Giard et al. 1988; Allamandola, Tielens, & Barker 1989) is now well established (cf. Lee & Wdowiak 1993a and references therein). Thus, PAHs can produce FUV extinction curvature (Buss et al. 1994), as is expected by conservation of energy from FUV absorption to IR emission.

To represent gaseous PAH extinction, we fit the observed 1700–1000 Å extinction deviation toward HD 37903 in the NGC 2023 molecular cloud (Buss et al. 1994), omitting the strong narrow stellar features at C IV, Si IV, and Lyα (Fig. 4). The deviation is negative below 6.8 μm^{-1} because the 2175 Å bump contributes to this extinction and is narrower in reflection nebulae (cf. Mathis 1994) as a result of photoevaporation of coatings on carbonaceous grains responsible for the 2175 Å bump.

The HD 37903 (B1.5 V) radiation is similar to HD 45677 and could produce a similar FUV dust extinction. We model empirically the observed HD 45677 extinction (Fig. 3) by scaling the HD 37903 deviation (Fig. 4) by 2.4 (and 1.3) times and adding it respectively to $R_V = 4$ (and $R_V = 5$) CCM extinctions (Fig. 3). Remarkably, the *models with additional PAH extinction agree much better with observed extinctions than do pure R_V extinctions*, particularly where the HD 45677 line blanketing is minimal. Between 7.8 and 9.1 μm^{-1} and near Lyβ at 9.75 μm^{-1}, the observed extinction rises above the "R_V + hydrocarbons" model (Fig. 3; *solid, smooth*) due to the apparent flux excess in HD 200775 between 1120 and 1180 Å and line blanketing from the HD 45677 disk: Si III λ1110, Fe II + Fe III λ1129, S III λ1191. The possible excess of ~14% in the HD 200775 spectrum from 8.5 to 9.1 μm^{-1} would translate into 0.20 and 0.11 on Figure 3 (shown as error bars) for $A_V = 0.7$ and 1.33 mag, respectively, and would contribute to most of the difference between the fit and the pseudocontinuum of the data.

To ensure that the PAH correction to the comparison star HD 200775 (Buss et al. 1994) did not cause much of the additional HD 45677 disk extinction, we performed the above division of spectra and subsequent R_V fitting while using a spectrum of HD 200775 that was not PAH–corrected. In this case, we found that no CCM curve fitted the resulting HD 45677 A_λ/A_V disk extinction, whether or not additional PAH extinction was used in the model.

Scattered light into the sight line would decrease, not

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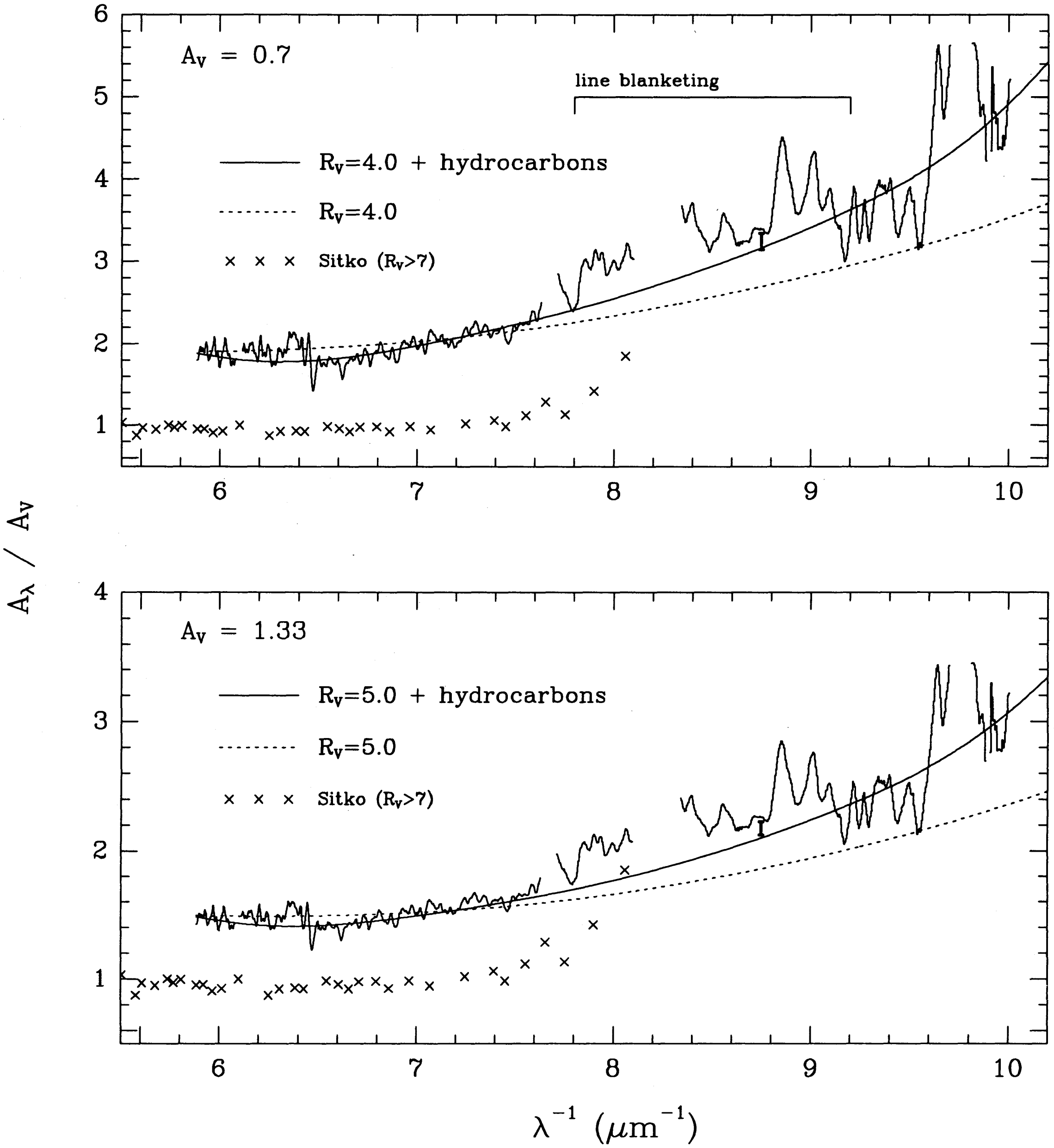

FIG. 3.—The lower and upper limits of the HD 45677 disk extinction (*solid*, *noisy*) derived for two values of A_V and smoothed by a five-point boxcar. Normal CCM ISM extinctions (*dashed*) fitted from 6 to 7.6 μm^{-1} cannot fit for wavenumbers greater than 7.5 μm^{-1}, but CCM extinctions with added PAH deviations (*solid*, *smooth*) better fit the observed extinctions except in regions of line blanketing. As the error bars show, eliminating the HD 200775 flux excess from 8.5 to 9 μm (cf. Fig. 2) would lower the HD 45677 extinction by 0.2 (A_V = 0.7) and 0.1 (A_V = 1.33). The Sitko et al. (1994; their Fig. 3 with Δ mag/ΔV) extinction (*crosses*), derived from observations of visually optically thick HD 45677 disk extinction, samples those regions of the disk with larger grains.

increase, the derived HD 45677 extinction because absorption would be dominant. However, we call the optical dimming of HD 45677 extinction rather than absorption because several pieces of evidence suggest that there is little light scattered by the disk (cf. Sitko et al. 1994) or the bipolar wind into the HD 45677 sight line at the time of the Astro-1 observations. Longward of 1400 Å (7 μm^{-1}), WUPPE polarimetry (Schulte-Ladbeck et al. 1992) indicates a scattered-light contribution of less than 1.5% on the HD 45677 flux, and from 1200 to 1300 Å, *IUE* spectra at different epochs show significant scattered light only near optical minimum (Pérez et al. 1994). Moreover, because the 1100–1800 Å scattering cross section of ISM dust is flat (Murthy et al. 1993), with declining albedo (Witt et al. 1993), the negligible mid-UV scattering in HD 45677 implies that the FUV scattering below λ < 1300 Å is also negligible in HD 45677. If grains were larger in the HD 45677 disk than in the ISM, the FUV scattering albedo would be even smaller (cf. Witt et al. 1993).

3.4. *Ionization and Dehydrogenation of PAHs*

We find that the hot, intense-UV radiation of HD 45677 suppresses some laboratory PAH IR emission and UV absorption features from the circumstellar spectrum.

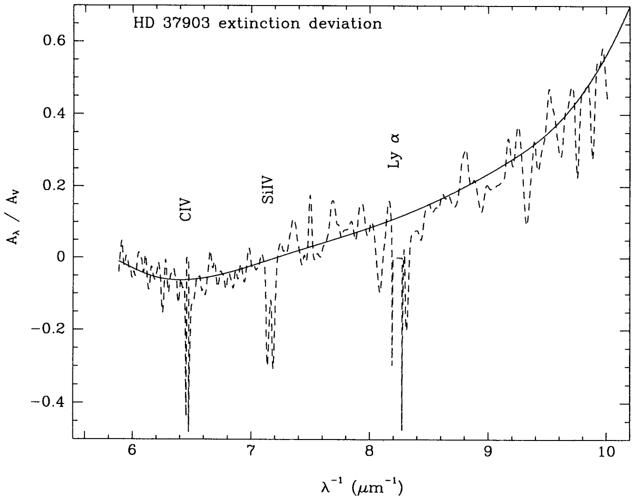

FIG. 4.—The extinction curve of HD 37903, minus the extinction of CCM, results in an extinction deviation (*dashed, noisy*) due to addtional extinction from PAHs and a lesser extinction due to a weaker 2175 Å bump. After omitting the strong, narrow, stellar features at C IV, Si IV, and Lyα, the fit (*solid, smooth*) is scaled and added to the model extinctions in Fig. 3.

Like the Galactic diffuse-medium extinction (Mathis 1990), the HD 45677 disk extinction has no strong narrow absorption features in the mid- to near-UV (2000–3200 Å) but has an increase in the FUV (Fig. 2). The FUV extinction from a mixture of laboratory unionized, neutral PAHs rises in the FUV (Joblin, Leger, & Martin 1992), but neutral PAHs produce additional sharp absorption features in the UV, such as a naphthalene feature at 2116 Å (Salama & Allamandola 1992) and a coronene $C_{24}H_{12}$ feature at ~2000 and 3000 Å (Lee & Wdowiak 1993a). As shown in these laboratory spectra, however, the ionization of PAHs, particularly the larger ones, weakens the mid-UV absorption features. Thus, ionized PAHs rather than neutral PAHs seem to be present around HD 45677, producing the continuous, rising FUV extinction.

In the IR, PAHs have emission bands (Flickenger, Wdowiak, & Gomez 1991) at 3.29 μm from a C–H stretch, at 6.2 μm and from 7.6 to 8.0 μm from C–C stretches, at 8.7 μm from a C–H in-plane bend, and at 11.2 μm from a C–H out-of-plane bend (Allamandola et al. 1989). If HD 45677 had the same ratio of 3 μm continuum to 3.3 μm feature strength as other Herbig Be stars (Brooke, Tokunaga, & Strom 1993), Allen et al. (1982) should have detected the 3.3 μm hydrocarbon emission around the IR bright HD 45677 in their 3.3 μm survey. The removal of an electron from a large PAH molecule disturbs the electronic structure and UV electronic transitions (Lee & Wdowiak 1993a), but vibrational modes and transitions resulting in IR emission should remain similar, and a 3 μm band should appear for ionized PAHs. However, dehydrogenation of PAHs, wherein the C–H bonds of PAH molecules are destroyed in intense UV fields, can suppress the C–H IR emission (Bregman et al. 1989; Allamandola et al. 1989).

We now show that the HD 45677 disk is likely to suffer dehydrogenation of PAHs. For a star like HD 45677 with a $T_{\rm eff} = 20{,}000$ K, Brooke et al. (1993) calculate that stellar radiation would dehydrogenate PAH molecules out to $R_{\rm CH} \approx 14{,}000$ AU in an optically thin disk with $n_0(H) = 5 \times 10^4$ cm^{-3}. This in turn would inhibit the spectral features related to the C–H bonds, although one should still observe those features related to the C–C bonds. For $\tau_{1100\,\text{Å}} \approx 2.3$ through the HD 45677 disk, $R \approx R_{\rm CH} \exp(-\tau) = 1400$ AU. If the HD 45677 disk H density were higher,

$$R(n) \approx R\left[\frac{n_{\rm disk}}{n_0({\rm H})}\right]^{-1/4} \tag{1}$$

for an edge-on disk.

The HD 45677 disk radius is smaller than 2000 AU because unpublished imaging (Schulte-Ladbeck et al. 1992 and references therein) shows that the disk of HD 45677 has an angular size of less than about 3.4 arcsec. Adopting $M_V = -3.0$ mag for a B2 V star, $V_0 = 8.13$ mag, and $A_V \geq 0.7$ mag in the HD 45677 disk (see § 3.3), we find that HD 45677 is, at most, at a distance of 1200 pc, which gives a maximum upper-limit disk radius of 2000 AU. (The height of the disk is of order $h = t \sin\theta = 1.4 \times 10^{15}$ cm, where t corresponds to the 0.1 arcsec thickness at 50° inclination from the disk plane [DeWarf & Dyck 1993; cf. Schulte-Ladbeck et al. 1992], which has dust as close as 1.8×10^{14} cm to the central star [McGregor et al. 1988]). Using our N(H I) $= 3.2 \times 10^{21}$ cm^{-2} for the HD 45677 disk (see § 3.2) and $R_{\rm disk} \leq 3 \times 10^{16}$ cm, gives a lower limit of $n_{\rm disk}({\rm H}) > 1 \times 10^5$ cm^{-3}. Since this n(H) is twice that of the Brooke et al. (1993) dehydrogenetion model, the HD 45677 dehydrogenation radius is $R(n) = 1200$ AU, by using equation (1). Thus, PAHs in the HD 45677 disk may be dehydrogenated along 60%–100% of the sight line through the HD 45677 disk, and would decrease the detectability of the PAHs at 3.3 μm.

4. DISCUSSION

In the intermediate-mass system of HD 45677, planetesimal formation appears to proceed by grain coagulation, similar to that in low-mass systems such as the solar system. In the high UV-radiation environment around HD 45677, the star evaporates PAHs off grains and dehydrogenates them, and destroys other volatile molecules such as H_2, CO, and probably ices—as opposed to the expected presence and condensation of these species in the outer regions of low-mass systems.

4.1. *Evolution of Grains*

The extremely large inferred $R_V > 7$ for grains in the more opaque regions of the HD 45677 disk shows an evolutionary growth of these grains, because R_V increases as grain sizes increase (CCM; Mathis 1990). Compared to the average in the diffuse ISM ($R_V = 3.1$) and in molecular clouds ($R_V \leq 5.6$; Cardelli & Clayton 1991), where grains have maximum sizes of 0.2–0.5 μm, these HD 45677 disk grains have sizes $a \geq 1$ μm (Sitko et al. 1994) and appear to be evolving toward planetesimals. This evolution results in fewer but larger grains if the grains coagulate (CCM). Radiative sweeping of small grains (Sitko et al. 1994) could also raise R_V and the mean grain size, but our detection of small grains ($R_V \approx 4$–5) for a period of moderate extinction shows that *coagulation, not sweeping, has created large grains in the HD 45677 disk.* Moreover, the effective temperature ($\geq$20,000 K) and mass ($\approx 8\ M_\odot$) of HD 45677 imply that the star will reach the main sequence within 4×10^4 yr of its birth (Palla & Stahler 1993). Thus, either the grains grew quickly in the disk during the collapse or large mantles had already grown on grains within the parent molecular-cloud core before the disk formed. Such mantles on the HD 45677 grains would have to contain mainly refractory elements rather than volatile gases, which seems at odds with molecular cloud chemistry. Coagulation of micron-sized grains in molecular clouds is unlikely (Choksi, Tielens, & Hollenbach 1993; Ossenkopf 1993), but fluffy or fractal grains might coagulate during the collapse of the protostellar cloud (Weidenschilling & Ruzmaikina 1994) on 10^6 yr timescales. In conclusion, it seems most plausible that the large disk grains form by coagulation during the collapse but might continue to grow during the short-lived disk phase.

It is unknown whether planets have time to form around intermediate-mass stars, but the growth of grains into planetesimals might be similar around both mid- and low-mass stars. The inner planets of our low-mass solar system are thought (Lissauer 1993) to form around rocky cores that are constructed by gravitational gathering of planetesimals, which themselves form through the collisional clumping of small grains into increasingly larger grains. Nevertheless, gas condensation and mantling onto grains can occur in low-mass systems, and Jovian outer planets are believed to form around icy cores of much larger mass (Lissauer 1993) that gravitationally sweep up gases such as H and He into their atmospheres. As we shall see, for the intermediate-mass HD 45677, such condensation and sweeping might be inhibited in the disk.

4.2. *Evolution of Gas and Condensates*

The gaseous component in the intermediate-mass system HD 45677 lacks some of the volatiles found in low-mass systems and molecular clouds. The fraction of hydrogen nuclei in H_2 to the total hydrogen $\{f = 2N(\mathrm{H_2})/[2N(\mathrm{H_2}) + N(\mathrm{H\ I})]\}$ for HD 45677 shows that the disk $f \leq 1.5 \times 10^{-2}$ is much smaller than that found in molecular clouds ($f = 0.5$) or even some diffuse ISM ($f \approx 0.05$) (Buss et al. 1994). McGregor et al. (1988) observed no CO lines from HD 45677, consistent with our nondetection of H_2 because H_2 has a smaller dissociation energy (4.477 eV) than CO. Thus, HD 45677 has photodissociated most of the H_2 and CO out of which the system formed, or else the rapid collapse and accretion in the HD 45677 disk has somehow dissociatively shocked the gas (cf. Neufeld & Hollenbach 1994). It would difficult, however, for the dense ($n > 10^5$ cm^{-3}) gas to remain dissociated in the presence of grains. The radiation is still responsible for the observed dissociation.

We infer the presence of PAHs in the HD 45677 disk gas from the disk FUV extinction (cf. Buss et al. 1994), not from any specific IR emission bands. Though the detected PAH extinction resembles that in a reflection nebula, the observed HD 45677 PAHs do not reside in an ISM molecular cloud because H_2 absorption is absent in the HD 45677 spectrum: HD 45677 has apparently drifted from its nursery cloud, analogous to the drifts in the Orion complex (cf. Maddalena et al. 1986). As evidence of further evolution from molecular cloud material, the HD 45677 star has also ionized and dehydrogenated the disk PAHs to the point that specific PAH features might be detectable only with high-resolution IR spectra at 6.2 μm and from 7.6 to 8.0 μm.

Both Schutte et al. (1990) and Brooke et al. (1993), however, have observed PAHs in the IR toward other Herbig Be stars, leading Natta, Prusti, & Krügel (1993) to suggest that PAHs might be an important component of many Herbig Be stellar disks. Since PAHs will probably be ionized and dehydrogenated around those hot stars with optically thin disks in the UV, the 20% detection rate of hydrogenated PAHs around intermediate-mass young stars (Brooke et al. 1993) could mean that most of these stellar disks have weak-to-moderate UV shielding. Thus, PAHs could be present, yet undetected at 3.3 μm, in many of the surveyed Herbig Be systems, particularly if interstellar 3.3 μm PAH emission contaminates the circumstellar emission of other Herbig Be stars. In practice, though, the actual yet unknown sizes and densities of the disks of intermediate-mass stars will determine the shielding.

Gaseous molecular PAHs increase the FUV extinction, while condensed PAHs decrease the FUV extinction (Buss et al. 1994). Small solid-state hydrocarbons, if present, might also contribute to FUV extinction (cf. Witt et al. 1993) but are not volatile. Like the star HD 37903, HD 45677 appears to be photoevaporating partially or wholly dehydrogenated hydrocarbons from grain surfaces so that the molecules are primarily gaseous rather than condensates. Thus, the disk PAHs, relative to the large grains, evolve like those in the ISM, evaporating into the gas phase under FUV irradiation from stars of B1.5–B3 type (Buss et al. 1994). Although grain growth in the HD 45677 disk probably decreases the underlying FUV extinction (CCM), we measure a PAH extinction excess of 1.3–2.4 times the excess extinction in the ISM near HD 37903. Thus the FUV radiation of HD 45677 is effective at keeping PAHs gaseous despite the growth of grains in the HD 45677 disk.

In addition to inhibiting the condensation of PAHs, the HD 45677 FUV radiation is likely to suppress condensation of the voltiles H_2 and CO. Thus, the lack of these gases in the disk is due to dissociation rather than condensation. The growth of grains producing the low 6–8 μm^{-1} extinction and large R_V value in the Sitko et al. (1994) extinction curve therefore occurs by coagulation, not by mantling of gas. Preferential radiative sweeping of small grains might be happening, but our own extinction (Fig. 3, $R_V \approx 4$–5) implies not only the continued presence of small grains, but also the formation and destruction of the large grains by collisions. In HD 45677, the strong radiation field might prevent the formation of ices and in turn hamper the formation of Jovian mass planets, particularly because H I is less massive than H_2 and harder to capture in an atmosphere. For stars hotter than B1.5 ($T \geq 25{,}000$ K), the harder FUV radiation can destroy PAHs (Buss et al. 1994) and their FUV shielding, further photodissociating molecules and inhibiting the formation of gas giants around young massive stars.

Furthermore, because PAHs are primarily gaseous, they might not directly participate in the planetesimal construction in medium-mass systems such as HD 45677. Rather than hydrocarbons being incorporated as PAHs in grains (Clemett et al. 1993), or alkanes into meteorites, as Lee & Wdowiak (1993b) speculate about providing complex organic molecules on the early Earth, the gaseous PAHs orbiting HD 45677 would have to be gravitationally captured or formed (Sagan et al. 1993) to be incorporated into planets, and even then the aromatics would initially lack hydrogen. Though it is unknown whether planets can form around intermediate-mass stars, the HD 45677 large grains suggest that rocky planets potentially could form but that gas-giant formation would be more difficult. It will be interesting to see if other intermediate-mass young stars have disks similar to that of HD 45677.

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REFERENCES

Allamandola, L. J., Tielens, A. G. G. M., & Barker, J. R. 1989, ApJS, 71, 733

Allen, C. W. 1981, Astrophysical Quantities (3d ed.; London: Athlone), 70

Allen, D. A., Baines, D. W. T., Blades, J. C., & Whittet, D. C. B. 1982, MNRAS, 199, 1017

Altenhoff, W. J., Braes, L. L. E., Olnon, F. M., & Wendker, H. J. 1976, A&A, 46, 11

Bibo, E. A., & Thé, P. S. 1993, A&AS, 89, 319

Boggess, A., et al. 1978, Nature, 275, 372

Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132

Bregman, J. D., Allamandola, L. J., Tielens, A. G. G. M., Geballe, T. R., & Witteborn, F. C. 1989, ApJ, 344, 791

Brooke, T. Y., Tokunaga, A. T., & Strom, S. E. 1993, AJ, 106, 656

Burnichon, M. L., Chalonge, D., Divan, L., & Swings, J. P. 1967, J. Obs. 50, 391

Buss, R. H., Jr., Allen, M., McCandliss, S., Kruk, J., Liu, J.-C., & Brown, T. 1994, ApJ, 430, 630

Cardelli, J. A., & Clayton, G. C. 1991, AJ, 101, 1021

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245 (CCM)

Choksi, A., Tielens, A. G. G. M., & Hollenbach, D. 1993, ApJ, 407, 806

Clemett, S. J., Maechling, C. R., Zare, R. N., Swan, P. D., & Walker, R. M. 1993, Science, 262, 721

Davidsen, A. F., et al. 1992, ApJ, 392, 264

DeWarf, L. E., & Dyck, H. M. 1993, AJ, 105, 2211

Diplas, A., & Savage, B. D. 1994, ApJ, 427, 274

Feinstein, A., Garnier, R., Vogt, N., Heck, A., Manfroid, J., & Swings, J. 1976, A&A, 51, 269

Flickenger, G. C., Wdowiak, T. J., & Gomez, P. L. 1991, ApJ, 380, L43

Giard, M., et al. 1988, A&A, 201, L1

Grady, C. A., Bjorkman, K. S., Shepherd, D., Schulte-Ladbeck, R. E., Pérez, M. R., de Winter, D., & Thé, P. S. 1993, ApJ, 415, L39

Halbedel, E. M. 1989, PASP, 101, 999

———. 1992, Inf. Bull. Var. Stars., 3602, 1

Harris, A. W., & Sonneborn, G. 1987, in Exploring the Universe with the *IUE* Satellite, ed. Y. Kondo (Dordrecht: Reidel), 729

Heck, A., Egret, D., Jaschek, M., & Jaschek, C. 1984, In *IUE* Low-Dispersion Spectra Reference Atlas-Part 1. Normal Stars (ESA SP-1052) (Noordwijk: ESA)

Herbig, G. H. 1959, ApJS, 4, 337

Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J. 1992, ApJ, 397, 613

Joblin, C., Léger, A., & Martin, P. 1992, ApJ, 393, L79

Kurucz, R. L. 1979, ApJS, 40, 1

Lee,W., & Wdowiak, T. J. 1993a, ApJ, 410, L127

———. 1993b, ApJ, 417, L49

Linsky, J. L., & Bohlin, J. N. 1993, in Proc. Ninth Workshop on the Vacuum Ultraviolet Calibration of Space Experiments (Boulder: National Center for Atmospheric Research)

Lissauer, J. J. 1993, ARA&A, 31, 129

Maddalena, R. J., Morris, M., Moscowitz, J., & Thaddeus, P. 1986, ApJ, 303, 375

Mathis, J. S. 1990, ARA&A, 28, 37

———. 1994, ApJ, 422, 176

Mathis, J. S., & Cardelli, J. A. 1992, 398, 610

McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988, ApJ, 324, 1071

Mendoza, E. E. V. 1958, ApJ, 128, 207

Morton, D. C., & Dinerstein, H. L. 1974, ApJ, 204, 1

Murphy, J., et al. 1993, ApJ, 408, L97

Natta, A., Prusti, T., & Krügel, E. 1993, A&A, 275, 527

Neufeld, D. A., & Hollenbach, D. J. 1994, ApJ, 428, 170

Olnon, F. M., & Raimond, E. 1986, A&AS, 65, 607

Ossenkopf, V. 1993, A&A, 280, 617

Palla, F., & Stahler, S. W. 1993, ApJ, 418, 414

Pérez, M. R., Grady, C. A., & Thé, P. S. 1993, A&A, 274, 381

Pérez, M. R., Grady, C. A., van der Ancker, M., Thé, P. S., de Winter, D., Schulte-Ladbeck, R. E., Bjorkman, K., & Shepherd, D. 1994, in Frontiers of Space and Ground-Based Astronomy: The Astrophysics of the 21st Century, ed. M. S. Longair, W. Wamsteker, & Y. Kondo (Dordrecht: Kluwer), in press

Pfau, W., Piirola, V., & Reimann, H.-G. 1987, A&A, 179, 134

Ryter, C., Puget, J. L., & Pérault, M. 1987, A&A, 186, 312

Sagan, C., Khare, B. N., Thompson, W. R., McDonald, G. D., Wing, M. R., Bada, J. L., Vo-Dinh, T., & Arakawa, J. L. 1993, ApJ, 414, 399

Salama, F., & Allamandola, L. J. 1992, ApJ, 395, 301

Savage, B. D., & Panek, R. J. 1974, ApJ, 191, 659

Savage, B. D., Wesselius, P. R., Swings, J. P., & Thé, P. S. 1978, ApJ, 224, 149

Schulte-Ladbeck, R. E., et al. 1992, ApJ, 401, L105

Schutte, W. A., Tielens, A. G. G. M., Allamandola, L. J., Cohen, M., & Wooden, D. H. 1990, ApJ, 360, 577

Siebemmorgen, R., & Krügel, E. 1992, A&A, 259, 614

Sitko, M. L., Halbedel, E. M., Lawrence, G. F., Smith, J. A., & Yanow, K. 1994, ApJ, in press

Sitko, M. L., & Savage, B. D. 1980, ApJ, 237, 82

Sitko, M. L., Savage, B. D., & Meade, M. R. 1981, ApJ, 246, 161

Snow, T. P., Jr., Buss, R. H., Jr., Gilra, D. P., & Swings, J. P. 1986, ApJ, 321, 921

Sorrell, W. H. 1989, MNRAS, 241, 89

Swings, J. P., & Allen, D. A. 1971, ApJ, 167, L41

Thé, P. S., de Winter, D., & Pérez, M. R. 1993, A&AS,

Walker, G. A. H., Yang, S., Fahlman, G. G., & Witt, A. N. 1980, PASP, 142, 411

Weidenschilling, S. J., & Ruzmaikina, T. V. 1994, ApJ, 430, 713

Whitcomb, S. E., Gatley, I., Hildebrand, R. H., Keene, J., Sellgren, K., & Werner, M. W. 1981, ApJ, 246, 416

Witt, A. N., et al. 1993, ApJ, 410, 714

Woodsworth, A. W., & Hughes, V. A. 1977, A&A, 58, 105