FULLY SAMPLED MAPS OF ICES AND SILICATES IN FRONT OF CEPHEUS A EAST WITH THE SPITZER SPACE TELESCOPE

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ABSTRACT

We report the first fully sampled maps of the distribution of interstellar CO$_2$ ices, H$_2$O ices, and total hydrogen nuclei, as inferred from the 9.7 /m silicate feature, toward the star-forming region Cepheus A East with the IRS instrument on board the Spitzer Space Telescope. We find that the column density distributions for these solid state features all peak at, and are distributed around, the location of HW2, the protostar believed to power one of the outflows observed in this star-forming region. A correlation between the column density distributions of CO$_2$ and water ice with that of total hydrogen indicates that the solid state features we mapped mostly arise from the same molecular clumps along the probed sight lines. We therefore derive average CO$_2$ ice and water ice abundances with respect to the total hydrogen column density of $X$(CO$_2$)$_{\text{ice}} \sim 1.9 \times 10^{-5}$ and $X$(H$_2$O)$_{\text{ice}} \sim 7.5 \times 10^{-5}$. Within errors, the abundances for both ices are relatively constant over the mapped region exhibiting both ice absorptions. The fraction of CO$_2$ ice with respect to H$_2$O ice is also relatively constant at a value of 22% over that mapped region. A clear triple-peaked structure is seen in the CO$_2$ ice profiles. Fits to those profiles using current laboratory ice analogs suggest the presence of both a low-temperature polar ice mixture and a high-temperature methanol-rich ice mixture along the probed sight lines. Our results further indicate that thermal processing of these ices occurred throughout the sampled region.

Subject headings: ISM: clouds — ISM: molecules — molecular processes

1. INTRODUCTION

Understanding how the structure and composition of ice mantles covering interstellar grains change with the local physical and chemical conditions is crucial to constraining the chemical evolution of protostellar envelopes, protoplanetary disks, and comets. Infrared observations toward low- to high-mass star-forming regions (e.g., Nummelin et al. 2001; Gibb et al. 2004) and quiescent molecular clouds (Whittet et al. 1998) using the Infrared Space Observatory (ISO) have shown that water (H$_2$O), carbon monoxide (CO), and carbon dioxide (CO$_2$) are common constituents of the ice mantles covering interstellar grains in dense molecular environments. While H$_2$O and CO are believed to form from grain surface reactions and gas-phase desorption, respectively (e.g., d’Hendecourt et al. 1985), the production of solid CO$_2$ remains uncertain. Mechanisms such as UV photolysis and/or grain surface chemistry are invoked. The routine detection of solid CO$_2$, with a fraction relative to water ice between 9% and 37% toward a number of star-forming regions (e.g., Gerakines et al. 1999; Nummelin et al. 2001), combined with the fact that CO$_2$ is easily produced via UV irradiation in the laboratory (Ehrenfreund et al. 1996), added weight to the suggestion that CO$_2$ ices are mainly produced via UV photolysis in the interstellar medium. However, the detection of CO$_2$ ice toward a number of quiescent clouds devoid of any embedded source of radiation, with abundances relative to water ice similar to those measured toward star-forming regions, demonstrated that production mechanisms such as grain surface reactions and gas-grain interaction need be considered too (Whittet et al. 1998, 2007).

A number of laboratory experiments studied the evolution of ice mixtures when subjected to thermal and/or UV processing (e.g., Ehrenfreund et al. 1996, 1999). Comparisons of these laboratory ice analogs with ISO and more recent Spitzer observations of interstellar ices allowed previous workers to better constrain the physical and chemical conditions in the clouds toward which these ices were detected (e.g., Ehrenfreund et al. 1998, 1999). In particular, the profile of the $v_3$ vibrational bending mode of solid CO$_2$ (15.2 /m) was found to be very sensitive to the composition of the ice mantle that the molecules are embedded in and to the thermal history of the region under study. Substructures that are characteristic of ice crystallization and segregation of the ice mantle constituents on thermal processing have been routinely used to constrain the physical and chemical environments around young stellar objects (e.g., Boogert et al. 2000; Gerakines et al. 1999; Boonman et al. 2003; Gibb et al. 2004; Bergin et al. 2005). These previous studies were all based on pointed observations of individual discrete sources, and thus require observations of multiple sources to provide any spatial information. With the Spitzer spectral mapping capability, one can now investigate the distribution of interstellar ices within a given dense cloud or star-forming region with unprecedented spatial sampling ($\sim 3''$). This provides a new opportunity to link the spectral properties of the ices with local physical conditions, and thus to throw new light on their origin and evolution. In this paper, we report on the spatial distribution and the evolution of the interstellar ices present toward the star-forming region Cepheus A East using this new capability offered by Spitzer.

Cepheus A is a well-known site of star formation located at a distance of about 650 pc. The region contains a series of deeply embedded far-infrared and radio-continuum sources, one of which...
dominates the luminosity of the entire region (HW2 with $2.5 \times 10^4 L_\odot$; Hughes & Wouterloot 1984; Lenzen et al. 1984; Evans et al. 1981). Ground-based (e.g., Hartigan et al. 1996; Goetz et al. 1998) and space-based observations (e.g., Wright et al. 1996; van den Ancker et al. 2000) revealed the existence of a multipolar outflow exhibiting complex structures of shock-excited atomic and molecular gas components, indicating the presence of both dissociative (J-type) and nondissociative (C-type) shocks resulting from successive episodes of activity (Narayanan & Walker 1996). The protostellar object HW2 was found to be the dominant powering source of the extremely high-velocity (EHV) outflow oriented northeast (NE), while the source (or sources) of the high-velocity jet (HV; oriented southeast) is still under debate (e.g., Goetz et al. 1998; Hiriart et al. 2004; Codella et al. 2003; Martin-Pintado et al. 2005).

Previous observations using ISO exhibited a number of absorption bands due to the presence of ice mantles containing CO, CO$_2$, and H$_2$O and due to silicate grains over the NE side of this star-forming region (van den Ancker et al. 2000). The CO and CO$_2$ ice abundances— with respect to water ice and averaged over the ISO Short-Wavelength Spectrometer (SWS) aperture—were found to be within the range observed toward other sight lines (e.g., Whittet et al. 1996). Using new high-resolution Spitzer data, we recently reported the first detection of gas-phase CO$_2$ emission. This emission extends over a $35'' \times 25''$ region associated with the EHV outflow (Sonnentrucker et al. 2006). We determined that the gaseous CO$_2$ molecules mostly result from sputtering of ice mantles due to interactions between the EHV outflow and the ambient medium. We derived a CO$_2$ gas-to-ice ratio of at most 3% over the region showing CO$_2$ gas emission.

Our data also exhibit strong absorption from the 15 $\mu$m CO$_2$ ice bending mode, from the 6 $\mu$m water ice band, and from the 9.7 $\mu$m silicate feature at the position of HW2 and at numerous spatial positions preferentially located away from the EHV outflow region. In this paper, we discuss the distribution of the solid state features observed toward Cepheus A East with the Spitzer Infrared Spectrograph (IRS). While H$_2$S(0) to S(7), [Ne ii], [Ne iii], [S i], [S ii], and [Fe ii] emissions as well as emission from C$_2$H$_2$ (Sonnentrucker et al. 2007) are also detected in our data, we focus here on the study of the absorptions from CO$_2$ ices, H$_2$O ices, and silicate grains—the latter used to estimate the total column density of hydrogen nuclei N(H$_\text{tot}$)—toward Cepheus A East. Section 2 summarizes our observations and §3 describes our data analysis. Section 4 compares the spatial distribution of the CO$_2$ ice, H$_2$O ice, and silicate grains with that of the quiescent molecular clouds present in this region. Section 5 discusses the ice abundances as well as the variations in ice mantle composition derived from fits to representative CO$_2$ ice profiles using current laboratory ice analogs.

2. OBSERVATIONS AND DATA REDUCTION

Spectral maps of two overlapping $1'\times1'$ square fields were obtained toward Cepheus A East with the IRS instrument onboard the Spitzer Space Telescope (Spitzer) as part of Guaranteed Time Observer (GTO) program 113. The short-low (SL, both orders), short-high (SH), and long-high (LH) modules allowed for wavelength coverage from 5.2 to 37 $\mu$m. Since the flux density at 25 $\mu$m exceeds the limit of 50 Jy, causing severe detector saturation, most of the LH data were not used. Continuous spatial coverage in the fields was obtained by stepping the slit perpendicular and parallel to its long axis in steps of half its width and 4/5 its length, respectively.

The data were processed at the Spitzer Science Center (SSC) using version 12 of the IRS pipeline. We used the Spectroscopy Modeling Analysis and Reduction Tool (SMART) software (Higdon et al. 2004) as well as a set of locally developed IDL routines (Neufeld et al. 2006) to extract wavelength-calibrated spectra, to remove bad pixels in the high-resolution modules, to calibrate the fluxes for extended sources, and to generate spectral line maps from the extracted spectra.

3. DATA ANALYSIS

Absorption caused by solid state features such as water ice (6.02 $\mu$m), amorphous silicates (9.7 $\mu$m), and CO$_2$ ice (15.2 $\mu$m) are clearly seen in most spectra. To compare the distribution of these ices with that of the gas-phase species known to result from interactions between the Cepheus A East outflows and the ambient molecular gas (e.g., Goetz et al. 1998; van den Ancker et al. 2000; Sonnentrucker et al. 2006), we derived the CO$_2$ ices, H$_2$O ices, and total hydrogen column densities as described below. Note that the absorption feature at 6.85 $\mu$m has an origin which remains uncertain (e.g., Keane et al. 2001; Gibb & Whittet 2002; Gibb et al. 2004); while certainly present in our spectra, this feature is not discussed here.

3.1. CO$_2$ and H$_2$O Column Densities

We derive the column densities ($N_m$) of solid CO$_2$ (15.20 $\mu$m) and H$_2$O (6.02 $\mu$m) by dividing the integrated optical depth profiles, in wavenumbers, by their respective molecular band strengths ($A_m$); $N_m = \langle 1/\tau \rangle \int \sigma(\tau) d\lambda/A_m$. We used third-degree polynomials to fit the local continuum around the 15 $\mu$m CO$_2$ ice bending mode and to derive the corresponding optical depth profiles. We adopted a band strength of $A_{CO_2} = 1.1 \times 10^{-17}$ cm molecule$^{-1}$ (Gerakines et al. 1995). Figure 1 displays an example of continuum fitting (top) and optical depth profile generation (bottom) for the CO$_2$ ice absorption observed in a summed spectrum at the position of the protostellar source HW2. This summed spectrum was obtained by adding the individual spectra contained in

![Fig. 1.—Top: CO$_2$ ice summed spectrum at the position of HW2 (J2000.0: $\alpha = 22^\text{h}56^\text{m}17.9^\text{s}$ and $\delta = +62^\circ01^\prime49^\prime$; Hughes & Wouterloot 1984). The thick smooth curve shows the best-fit continuum used to derive the optical depth profile with $\tau(\lambda) = \log I(\lambda)/I_\text{cont}$. The thin-dashed lines show the continuum best fit shifted by $\pm 1 \sigma$ used to estimate the CO$_2$ ice column density uncertainties. Bottom: Resulting optical depth profile for the best-fit continuum. The thick black segment delineates the wavelength range over which the optical depth integration was performed in all cases.](image)
a 6′′ × 8′′ region centered on HW2. In the top panel, the thick smooth curve superimposed on the summed spectrum represents the best fit to the local continuum at this spatial position. In the bottom panel, the thick horizontal segment shows the wavelength range over which the CO2 optical depth profile was integrated to derive the corresponding CO2 column density.

Because of the complex structure present in the continuum around the 6 μm water ice absorption feature, we constrained the local continuum fit using two narrow wavelength ranges that appeared to be the least affected by intervening species (from 5.2 to 5.7 μm and from 7.4 to 7.6 μm). To produce the water ice optical depth profiles, we fitted these continuum windows using a linear combination of a first-order polynomial and a Gaussian function with fixed width and fixed line center to account for emission arising from the H2 S(7) line at 5.52 μm. We adopted a H2O band strength of A_{H2O} = 1.2 × 10^{-17} cm molecule^{-1} (Gerakines et al. 1995) to derive the water ice column density in the mapped region.

To estimate the uncertainties in column density introduced by our fits to the continuum local to the CO2 and H2O ice features, we first calculated the standard deviation (σ) around our best-fit continuum in each continuum window. We then shifted the best-fit continuum by ±1σ and generated the corresponding optical depth and new estimate of the ice column densities. The difference between the best-fit column density and the columns obtained by shifting the best-fit continuum model constitutes our ±1σ error in N(CO2)ice and N(H2O)ice. The dashed lines in the top panel of Figure 1 show the shifted model continuum we used to estimate the ±1σ uncertainty in the CO2 ice column density for this particular summed spectrum. We used that same technique to derive the 1σ uncertainty in the H2O ice column densities.

3.2. Hydrogen Column Density

Because direct measurements of the total hydrogen column density are not possible toward the region we mapped, we estimated the total column density of hydrogen nuclei by fitting the observed 9.7 μm silicate absorption feature (SL1 data alone) with a linear combination of (1) a first-order polynomial; (2) the renormalized synthetic Galactic extinction curve per unit hydrogen column calculated for $R_V = A_V/E_{B-V} = 5.5$ (Weingartner & Draine 2001; Li & Draine 2001; Draine 2003a, 2003b); and (3) three Gaussian functions with fixed widths and centroids to account for emission from the H2 S(4), H2 S(2), and [Ne II] lines (8.02, 12.24, and 12.81 μm, respectively). Because numerous silicate features show signs of saturation in their cores toward Cepheus A East, we restricted our fits to the wings of the observed silicate profiles (from 7.7 to 8.95 μm and 12 to 14 μm). Note also that our fitting model assumes that most of the dust resides in a cold foreground component with no significant contribution of background emission from hot dust. If there were underlying silicate emissions produced by hot dust in addition to the absorption due to cold dust, then one should regard our hydrogen column density estimates as lower limits to the true columns along the probed sight lines containing hot dust (Gillett et al. 1975). Figure 2 displays examples of best fits (red curves) to the observed 9.7 μm silicate profile (black curves) at two spatial positions: the region around the protostellar source HW2 believed to power the EHV outflow (top), and the region around two radio-continuum sources (HW5 and HW6) where interaction between the EHV outflow and the ambient material is believed to take place (bottom; see also Goetz et al. 1998; Sonnentrucker et al. 2006).

We also produced an additional set of fits to the observed silicate profiles using the synthetic Galactic extinction curve per unit hydrogen column calculated for $R_V = 3.1$ in order to assess the impact that dust properties have on our hydrogen column density estimates. We find that the hydrogen columns derived assuming dust properties consistent with $R_V = 3.1$ are systematically greater by ∼18% than those derived assuming $R_V = 5.5$. Thus, while the dust properties adopted to fit the observed silicate features do affect the overall hydrogen column density scale we derived, these assumptions do not affect the local spatial variations that we see in the N(H2O) distribution shown in Figure 3, assuming that the silicate profiles scale with N(H2O). Since a number of studies suggested that the average Galactic extinction curve calculated for $R_V = 5.5$ is most appropriate to describe the extinction properties of dense molecular clouds (e.g., Sharpless 1952; Vrba & Rydgren 1984; Whittet et al. 2001), we adopted the total hydrogen column densities obtained with the dust extinction properties corresponding to $R_V = 5.5$ for the remainder of our study. With the latter dust grain model, the extinction per hydrogen column has a value of 4.957 × 10^{-23} cm^2 H^{-1} at 9.7 μm (Draine 2003a, 2003b).

To estimate the uncertainties in the total hydrogen column density introduced by the adopted silicate profile fitting function, as before we calculated the standard deviation (σ) around our best-fit model to the observed silicate feature in a wavelength range between 13 and 13.95 μm in each case. We then increased the best-fit hydrogen column, N(H2O), by ±1, ±2, and ±3σ and compared these new fits to the observed silicate profiles. Our comparison indicates that a ±1σ error of at least 5% in the derived N(H2O)—as shown by the blue dash-dotted lines in Figure 2—often adequately reflects the uncertainties related to our silicate absorption model fits. We adopted these ±1σ errors on the hydrogen column densities in the subsequent sections when discussing the ice abundance distribution in Cepheus A East (see Figs. 5 and 6). Note that Chiar et al. (2007) recently reported the strength
Fig. 3.—Top left: Column density distribution of solid CO\textsubscript{2} (15.2 \textmu m) absorption. Bottom left: Column density distribution of silicates (9.7 \textmu m) tracer of N(H\textsubscript{tot}). Top right: Column density distribution of H\textsubscript{2}O ice (6.02 \textmu m). Bottom right: Continuum emission distribution at 14.95 \textmu m. The crosses indicate the positions of some of the known radio-continuum sources in this region. The coordinates are offsets in arcseconds in right ascension and declination with respect to HW2. The gray contours show the distribution of NH\textsubscript{3}(1,1) into three clumps of cold quiescent molecular gas, CepA-1, CepA-2, and CepA-3 (Torrelles et al. 1993). The lowest contours are 10 and 25 in steps of 25 mJy km s\textsuperscript{-1} beam\textsuperscript{-1}. The rectangles (top right) show examples of spatial regions over which individual IRS spectra were combined to generate the summed IRS spectra labeled a, b, P1, and P2. These regions are further discussed in \S\S 5.2 and 5.3. The summed spectra at P1 and P2 are shown in Fig. 4.
of the silicate feature to be systematically weaker relative to near-IR extinction in molecular clouds compared to diffuse clouds. Hence, an additional systematic source of error in our estimate of the total hydrogen column density could also arise from our adopted Galactic dense cloud extinction curve model.

4. RESULTS

Figure 3 shows the column density distributions we obtained toward the portion of the Cepheus A East map common to both the SL and SH modules for CO\textsubscript{2} ice (top left), water ice (top right), and total hydrogen—as inferred from the silicate absorption feature (bottom left). The gray contours display the spatial distribution of NH\textsubscript{3}(1,1) emission concentrated into three major clumps of cold quiescent molecular gas, CepA-1, CepA-2, and CepA-3 (Torrelles et al. 1993). The coordinates are offsets in right ascension and declination (e.g., van den Ancker/C22 continuum map/C14 4.—Summed IRS spectra of CO/C11 62; C14 ices compared to those observed for the H/C22 ice profile are also seen and are indicative of space/C22 9 2 regions centered on the radio-continuum/C14 5.4 and Gerakines et al. mC O m were combined with their corre-

ices and H/C22 6) position, and/C14 01) a n d P 2/C14 (SH), in each region centered on the marked positions in order to/C14 11 01) produce the EHV outflow (e.g., Goetz et al. 1998), in units of arcseconds. The crosses indicate the positions of some of the known radio-continuum sources in this region (Hughes & Wouterloot 1984). The rectangles (top right) show examples of spatial regions over which individual IRS spectra were summed to generate the regions labeled a, b, P1, and P2 (see §§ 5.2 and 5.3 below).

In general, the CO\textsubscript{2} ice, H\textsubscript{2}O ice, and total hydrogen column density distributions peak at, and closely around, the position of the still deeply embedded protostellar source HW2 where substantial extinction ($A_V > 75$ mag; Lenzen et al. 1984) allows for a significant ice buildup associated with the NH\textsubscript{3}(1,1) clump labeled CepA-1 to occur (Torrelles et al. 1993). There seems to be no clear association between the ice distributions and the two other NH\textsubscript{3}(1,1) clumps CepA-2 and CepA-3 where outflow interactions have been previously reported (e.g., Goetz et al. 1998; Sonnentrucker et al. 2006). In addition, local differences in the ice distributions seem to exist, the most striking being the very patchy and somewhat more extended structures observed for the CO\textsubscript{2} ices compared to those observed for the H\textsubscript{2}O ices and the silicates around the CepA-1 clump as well as the weak water ice absorption compared to CO\textsubscript{2} ice over the region labeled P2.

The bottom right panel of Figure 3 displays the background emission distribution, in logarithmic scale, derived from a linear fit to the continuum local to the CO\textsubscript{2} ice feature and centered at 14.95 $\mu$m. This map (together with the 7.5 $\mu$m continuum map not displayed here) shows that continuum dust emission is present throughout the observed region. The overall spatial variations exhibited by the silicate and the two ice maps are, therefore, not due to a lack of dust continuum emission against which to absorb background light. Previous observations established the presence of an IR reflection nebula located a few arcseconds north of HW2, which scatters the radiation emanating from the HW2 protostellar region (e.g., Lenzen et al. 1984; Goetz et al. 1998). The extent and peak position of the dust emission we measure are consistent with those of this reflection nebula, indicating that the dust continuum emission shown here originates from that same region.

Figure 4 displays examples of summed spectra in the 5.2–17 $\mu$m range at five positions indicated in the maps of Figure 3. We generated these data by adding all individual spectra included in a $\sim 6'' \times 8''$ region centered on the marked positions in order to increase the lines signal-to-noise ratio (S/N) and minimize effects due to the difference in spatial resolution between the low- and high-resolution data. Low-resolution summed spectra from 5.2 to 11 $\mu$m (SL, 2 orders) were combined with corresponding

summed high-resolution spectra from 11 $\mu$m on (SH), in each case. These five spectra were chosen to be representative of the local spatial variations observed in both the gas-phase and the solid state content. In particular, note the complete absence of gas-phase emission features but the presence of strong solid state absorption features at the HW2 position, in contrast with the rich gas-phase spectrum and the weak ice features at the NE position. A comparison of positions P1 and P2 further illustrates potential local spatial variations in the CO\textsubscript{2} ice and H\textsubscript{2}O ice contents, as already suggested by the maps of Figure 3. Finally, variations in the 15.2 $\mu$m CO\textsubscript{2} ice profile are also seen and are indicative of spatial changes in the ice mantle composition and/or in the thermal history of this star-forming region (see § 5.4 and Gerakines et al. 1999; Gibb et al. 2004).

5. DISCUSSION

While absorption from solid H\textsubscript{2}O and solid CO\textsubscript{2} were previously measured toward this region using ISO (e.g., van den Ancker et al. 2000), the unparalleled Spitzer spatial resolution and its much greater sensitivity allowed us both to map and compare the distribution of these ices for the very first time over a much larger spatial extent than was previously possible. Because the H\textsubscript{2}O ice, the total hydrogen, and the CO\textsubscript{2} ice column densities are obtained from different modules (SL and SH), we produced a set of contiguous summed spectra over the region mapped in both SL and SH in order to minimize the effects that different spatial resolution might have on the single-pixel extracted spectra and to increase the line S/Ns. A total of 28 such summed spectra were produced, five of which are shown in Figure 4. It is the column densities we derived from these contiguous summed spectra that
Ice Abundance

Ice abundance has been shown to be north of the observed C6 lines toward this region. We therefore find that the CO
distribution shows a mean abundance of 5.1. CO
masses showed that the column density derived from the 6 m water ice band was systematically overestimated by up to a factor 3 with respect to the column derived from the 3 m band toward YSOs (e.g., Keane et al. 2001; Gibb & Whittet 2002). The excess absorption coinciding with the 6 m water ice band was attributed to an intervening species, the origin of which remains unclear to date. The selective appearance of this additional absorption feature toward star-forming regions, however, led to the conjecture that these unidentified species might result from some energetic processing (Gibb & Whittet 2002).

Because of the Spitzer wavelength cutoff, the water ice column densities we derived from our data (see Fig. 3, top right) rely solely on the 6 m band measurements, and hence might potentially be overestimated if such blending were to occur in our spectra. Van den Ancker et al. (2000) observed part of the Cepheus A East with the ISO SWS 14′×27′ aperture centered on the infrared source IRS6a (Hughes & Wouterloot 1984). IRS6a is located at (Δα cos δ = +5.3′; Δδ = +11′), i.e., 4′ north of the radio-continuum source HW4 in our maps. Within errors, the CO2 ice column density increases with increasing total hydrogen column, as expected if both species arise predominantly from the same cold molecular clumps. Since some scatter does exist, we calculated the Pearson correlation coefficient to determine how significant this apparent correlation might be. With our sample size, a correlation coefficient of at least r = 0.48 would indicate that the probability for this correlation to be due to chance is less than 1%. We find a correlation coefficient of r = 0.83. Hence, our data show that the CO2 ice and the hydrogen column densities do increase together, thereby confirming that the two species predominantly arise from the same cold molecular clumps.

Recent observational results obtained toward intraclump molecular clouds (i.e., clouds devoid of embedded sources of radiation) confirmed that a minimum visual extinction $A_V = 4.3 \pm 1.0$ mag [corresponding to $N(H_{\text{tot}}) = 8.2 \times 10^{21}$ cm$^{-2}$; see Bohlin et al. 1978; Whittet et al. 2001] seems required for substantial CO2 ice to build up onto dust grains (e.g., Bergin et al. 2005; Whittet et al. 2007; see also Chiar et al. 1995). To determine whether this “threshold effect” pertains toward the Cepheus A East region, we searched for the linear combination that best fitted our data points. The best-fit combination to our measurements (Fig. 5, black line) has the form $N(CO_2)_{\text{ice}} = (1.9 \pm 0.4) \times 10^{-5} N(H_{\text{tot}}) - N_0$ with $N_0 = (2.6 \pm 2.2) \times 10^{22}$ cm$^{-2}$ (1 σ error bars). Considering our large uncertainties, the extinction threshold obtained from our best-fit line, while apparently higher, is not inconsistent with the extinction threshold determined previously.

In light of the overall good $N(CO_2)_{\text{ice}}$-$N(H_{\text{tot}})$ correlation exhibited by our data, we derived the CO2 abundance [X(CO2)$_{\text{ice}}$] by dividing $N(CO_2)_{\text{ice}}$ by its corresponding $N(H_{\text{tot}})$ toward our contiguous summed spectra. Because CO2 ice has been shown to build up on grains once the extinction threshold is reached, the slope of the linear relationship displayed in Figure 5 essentially measures the average CO2 ice abundance for the region we sampled with Spitzer toward Cepheus A East. We therefore find that the CO2 ice distribution shows a mean abundance of $X(CO_2)_{\text{ice}} = (1.9 \pm 0.4) \times 10^{-5}$, which is consistent with abundances either measured previously (e.g., van Dishoeck et al. 1996; Boogert et al. 2004) or predicted by chemical models allowing for efficient surface diffusion to occur (e.g., Charnley 1997; Ruffle & Herbst 2001).

5.2. H2O Ice Abundance

ISO observations of the 3.05 and 6.02 μm water ice bands toward a sample of sight lines comprising quiescent molecular clouds as well as young stellar objects (YSOs) of intermediate and high masses showed that the column density derived from the 6 m water ice band was systematically overestimated by up to a factor 3 with respect to the column derived from the 3 μm band toward YSOs (e.g., Keane et al. 2001; Gibb & Whittet 2002). The excess absorption coinciding with the 6 μm water ice band was attributed to an intervening species, the origin of which remains unclear to date. The selective appearance of this additional absorption feature toward star-forming regions, however, led to the conjecture that these unidentified species might result from some energetic processing (Gibb & Whittet 2002).

Because of the Spitzer wavelength cutoff, the water ice column densities we derived from our data (see Fig. 3, top right) rely solely on the 6 μm band measurements, and hence might potentially be overestimated if such blending were to occur in our spectra. Van den Ancker et al. (2000) observed part of the Cepheus A East with the ISO SWS 14′×27′ aperture centered on the infrared source IRS6a (Hughes & Wouterloot 1984). IRS6a is located at (Δα cos δ = +5.3′; Δδ = +11′), i.e., 4′ north of the radio-continuum source HW4 in our maps. In other words,
Fig. 6.—H$_2$O ice column density vs. total hydrogen column density. The best linear fit (solid line) to our data has the form $N$(H$_2$O)$_{\text{ice}}$ = $(7.5 \pm 1.7) \times 10^{-5} [N(H_{\text{tot}}) - (2.3 \pm 2.5) \times 10^{22}]$ ($\sigma$ error bars). As for water ice, once a minimum total hydrogen column density is reached the observed CO$_2$ distribution shows a fairly constant average abundance $X$(H$_2$O)$_{\text{ice}}$ = $(7.5 \pm 1.7) \times 10^{-5}$ with respect to $N$(H$_{\text{tot}}$) over the spatial region common to SL and SH observations. Departures from the mean distribution can be seen for the regions labeled a, b, and P1. Our current data do not allow us to determine whether these variations are real or due to blending of the water ice band with unidentified features.

The region over which the average ISO spectrum was obtained is included in our larger Spitzer map and covers most of the CepA-2 and CepA-3 NH$_3$(1,1) clouds as well as the EHV outflow region. A comparison of our water ice measurements based on the 6 $\mu$m band along with those obtained by van den Ancker et al. (2000) from both water ice features shows very good consistency over this common region within errors. Most importantly, van den Ancker et al. measured no difference between the 3 and 6 $\mu$m water ice column densities over this region, implying that no significant blending of the 6 $\mu$m ice feature occurs over the CepA-2, CepA-3, and EHV outflow regions.

In order to determine whether significant blending might occur over the CepA-1 NH$_3$(1,1) cloud where the water ice column is the highest in our data, we compared the water ice and total hydrogen column density distributions derived from our summed spectra. Figure 6 displays $N$(H$_2$O)$_{\text{ice}}$ versus $N$(H$_{\text{tot}}$) for the 28 contiguous summed spatial positions. Our data suggest that the water ice and the total hydrogen column increase in concert in the mapped region. For our sample, the Pearson correlation coefficient for water ice is $r = 0.76$, much higher than the minimum correlation coefficient required to ensure a chance probability lower than 1%. Hence our data indicate that the water ice and the hydrogen column densities do increase together, thereby implying that the two species predominantly arise from the same cold molecular clumps (as found for CO$_2$ ices).

As for CO$_2$ ice, we calculated the linear combination that best fitted our data points for water ice. The best-fit combination to our measurements (Fig. 6, solid line) has the form $N$(H$_2$O)$_{\text{ice}}$ = $(7.5 \pm 1.7) \times 10^{-5} [N(H_{\text{tot}}) - N_0]$ with $N_0 = (2.3 \pm 2.5) \times 10^{22}$ cm$^{-2}$ ($\sigma$ error bars). Departures from the best linear fit to our data are noticeable for three spatial regions marked a, b, and P1 (see Fig. 6). Inspection of the summed spectra indicates that these positions correspond to the peaks in H$_2$O ice column seen in Figure 3 (top right), at the location of the CepA-1 NH$_3$(1,1) clump. To our knowledge, no data containing the 3 $\mu$m water ice band are available over this particular region. We are thus unable to determine whether the local enhancements we observe in the water ice columns are real or due to blending with unidentified species. As in the case of the CO$_2$ ices, the best-fit line to the H$_2$O ice-total hydrogen relationship shows an intercept consistent (within large errors) with the water ice extinction threshold of 3.2 $\pm$ 0.1 mag and corresponding to $N$(H$_{\text{tot}}$) = $6.1 \times 10^{21}$ cm$^{-2}$, determined by Whittet et al. (2007).

In light of the good correlation between $N$(H$_2$O)$_{\text{ice}}$ and $N$(H$_{\text{tot}}$), we derived the water ice abundance [$X$(H$_2$O)$_{\text{ice}}$] by dividing $N$(H$_2$O)$_{\text{ice}}$ by its corresponding total hydrogen column density in all cases. The slope of the best-fit line displayed in Figure 6 indicates that the H$_2$O ice distribution shows an average abundance of $X$(H$_2$O)$_{\text{ice}}$ = $(7.5 \pm 1.7) \times 10^{-5}$, a value consistent with those observed elsewhere (e.g., Nummelin et al. 2001; Boogert et al. 2004) over the region mapped both in SL and SH. Within errors, the H$_2$O ice abundance excesses observed for the regions labeled a, b, and P1 again correspond to $N$(H$_2$O)$_{\text{ice}}$ $\geq$ $9 \times 10^{18}$ cm$^{-2}$, i.e., the high end of the water ice column density distribution where blending with unidentified features is most likely to have occurred.

5.3. Ice Evolution toward Cepheus A East

The formation, destruction, and evolution of ices are believed to be governed by relatively few processes intimately linked to the local physical conditions: (1) energetic processes involving UV photolysis and cosmic-ray bombardment; (2) grain surface reactions; (3) thermal processing of the ice mantles by embedded protostars; and (4) sputtering in shocks. Because CO$_2$ ices are readily formed via UV photolysis in the laboratory, this formation mechanism was favored to account for the routine detection of CO$_2$ ices toward star-forming regions. However, the detection of relatively high fractions of CO$_2$ ice relative to H$_2$O ice toward quiescent clouds and the intracloud medium indicated that CO$_2$ ices can be formed in environments devoid of embedded sources of radiation with a typical fraction with respect to water ice of 17% (e.g., Whittet et al. 1998, 2007; Bergin et al. 2005). Thus, CO$_2$ ice formation mechanisms other than UV photolysis need to be considered (e.g., Charnley 1997; Ruffle & Herbst 2001).

Figure 7 compares the column density distribution of CO$_2$ ices to that of water ice for the 28 contiguous summed spectra common to the SL and SH maps of Cepheus A East. The thick black line represents the typical ISM fraction of CO$_2$ ice with respect to water ice of 0.17 (Gerakines et al. 1999). The thin black line shows the best fit to our measurements, excluding regions a, b, and P1 where potential significant blending of the 6 $\mu$m water ice feature might occur. A slope of 0.22 $\pm$ 0.03 fits our data points best. We find a Pearson correlation coefficient of 0.77. For our sample size, this value is much greater than the minimum coefficient of 0.48 required for the correlation to be significant at a 1% level. Our data, therefore, indicate that the CO$_2$ ice and the water ice build up in concert onto dust grains under very similar physical conditions and that they essentially coexist in the same ice mixture. Our results strengthen the case that these two species formed together, as discussed by Bergin et al. (2005), with a CO$_2$ ice fraction with respect to water ice overall similar to those toward the typical quiescent molecular clouds studied so far (e.g., Whittet...
Laboratory experiments have shown that, on heating, ice mixtures with various concentrations of H$_2$O, CO$_2$, and CH$_3$OH undergo crystallization leading to an effective segregation of the ice constituents in the mixtures (Ehrenfreund et al. 1997, 1999). Observationally, such a phenomenon is detectable through the appearance of multiple substructures in the profile of the CO$_2$ ice bands. Such multiple-peaked structures cannot be produced by UV irradiation in the laboratory (Ehrenfreund et al. 1999). The profile of the CO$_2$ $\nu_2$ bending mode (15.2 $\mu$m) has been shown to be the most sensitive to the ice mantle composition and to the mantle thermal processing by nearby protostars. In particular, the presence of a sharp double-peak structure at ~15.2 $\mu$m along with a broader feature around 15.4 $\mu$m in the CO$_2$ profile has been recognized as a signature of thermal processing of ice mixtures containing roughly equal amounts of H$_2$O, CO$_2$, and CH$_3$OH.

The long-wavelength shoulder is characteristic of segregation of CO$_2$ and CH$_3$OH in the ice mantle on heating (Ehrenfreund et al. 1998). Comparisons of the observed 15.2 $\mu$m band profiles with laboratory interstellar ice analogs have subsequently led to a better understanding of the composition of interstellar ice mantles and have allowed us to constrain the local molecular environment these ice mantles are subjected to (Gerakines et al. 1999; Nummelin et al. 2001; Boogert et al. 2004; Bergin et al. 2005).

All CO$_2$ bands we mapped with sufficient S/N exhibit a sharp double-peak substructure along with a broad long-wavelength shoulder of variable intensity, as shown in Figure 4. To compare our observations with the currently available laboratory interstellar ice analogs (Ehrenfreund et al. 1997, 1999) we derived the CO$_2$ optical depth profiles by fitting a third-degree polynomial to the local continuum around the 15 $\mu$m band, and we adopted the fitting method described in Gerakines et al. (1999) to constrain the ice mantle composition toward Cepheus A East. Because the CO$_2$ ice bands expand over two SH orders which overlap around 15.2 $\mu$m, we only retained those spectra with the highest S/N and no apparent order-edge mismatches to ensure that the most accurate fits to both the band wings and the sharp substructures are...
obtained. Examples of such optical-depth spectra are shown in Figure 8 (black curves) along with their respective best laboratory ice analog fits (red curves).

In all cases, our best fits require two ice components at two different laboratory temperatures, a broad polar component \( (\text{H}_2\text{O}: \text{CO}_2 : \text{CO} = 100:20:3) \) at 20 K (Fig. 8, blue curve) and a triple-peaked methanol-rich mixture \( (\text{H}_2\text{O}: \text{CH}_3\text{OH}: \text{CO}_2 = 1:1:1) \) at 119 K (Fig. 8, green curve). From these best fits we estimate that the fraction of low-temperature ice present in the mantles ranges from 25% at the position of HW2 (Fig. 8, top) to 40% over the CepA-2 region (Fig. 8, bottom). To evaluate the robustness of our ice mixture solution and because the optical depth spectra are very sensitive to the continuum normalization, we produced a second data set using a spline function to fit the local continuum. We fitted this second set of optical depth spectra with the same ice mixtures and laboratory temperatures but allowed the cold-ice fraction to vary. The range in cold-ice fraction which led to these new best fits is reported in Figure 8 for each spectrum. Within the errors, our data indicate that the concentration of low-temperature ice is at least 30% over the four probed positions which were chosen to be representative of the ice composition over the mapped Cepheus region. Local variations in the low-temperature ice fraction seem to exist with a slight increase of this concentration when moving toward the CepA-2 clump and away from the NE outflow activity (Fig. 8, bottom two panels). The need for an increasingly large fraction of a high-temperature ice mixture containing methanol in the fits indicates that the ice mantles experienced significant thermal processing over the history of the region, leading to segregation of the \( \text{CO}_2 \) and methanol ices in the mantles.

6. CONCLUSION

We used new Spitzer data obtained with the IRS instrument to produce fully sampled maps of the distribution of \( \text{CO}_2 \) ices \( (15.2 \mu\text{m}) \), \( \text{H}_2\text{O} \) ices \( (6.02 \mu\text{m}) \), and total hydrogen nuclei, as inferred from the 9.7 \( \mu\text{m} \) silicate feature, toward the star-forming region Cepheus A East. We find that all solid state features peak at, and are distributed closely around, the spatial position of the deeply embedded protostar HW2 and coincide with the \( \text{NH}_3(1,1) \) molecular clump CepA-1. Otherwise, the distributions show column densities lower by about a factor 2 than those measured over the CepA-1 region.

The correlations we observe between the \( \text{CO}_2 \) ice, the \( \text{H}_2\text{O} \) ice column density distributions, and that of total hydrogen imply that the solid state features predominantly arise from the same molecular clouds along the probed sight lines. We hence derived the \( \text{CO}_2 \) and water ice abundances with respect to the measured total hydrogen column density at each summed spatial position in the map. We find an average \( \text{CO}_2 \) ice abundance of \( (1.9 \pm 0.4) \times 10^{-5} \) and an average \( \text{H}_2\text{O} \) ice abundance of \( (7.5 \pm 1.7) \times 10^{-5} \) over the probed region.

A comparison of the \( \text{CO}_2 \) and water ice column density distributions indicates that both ices build up onto dust grains in concert over the probed region. The fairly good correlation between the column densities of the two ices also indicates that blending of the water ice band by unidentified features is not significant in our data. Overall, we find that \( \frac{N(\text{CO}_2)}{N(\text{H}_2\text{O})} = (0.22 \pm 0.03) \times \frac{N(\text{H}_2\text{O})}{N(\text{H}_2\text{O})} \), a fraction similar to that typically found in the intercloud medium and toward quiescent molecular clouds (17%), suggesting that grain surface chemistry is the most likely production mechanism of \( \text{CO}_2 \) ices toward this region.

Best fits to the \( \text{CO}_2 \) ice bending mode using the current laboratory interstellar ice analogs database indicate that the ice mantles in Cepheus A East are composed of two ice mixtures, a low-temperature \( (T_{lab} = 20 \text{ K}) \) polar ice mixture and a high-temperature \( (T_{lab} = 119 \text{ K}) \) methanol-rich mixture. We find that while about 30% of the probed ice mantles is at low temperature, variations of the cold-ice fraction also seem to exist over the probed region. The presence of the high-temperature methanol-rich ice mixture is indicative of significant thermal processing of a fraction of these ice mantles over Cepheus A East history.

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