DETECTION OF ACETYLENE TOWARD CEPHEUS A EAST WITH SPITZER

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ABSTRACT

The first map of interstellar acetylene (C$_2$H$_2$) has been obtained with the Infrared Spectrograph on board the Spitzer Space Telescope. A spectral line map of the $\nu_3$ vibration-rotation band at 13.7 $\mu$m, carried out toward the star-forming region Cepheus A East, shows that the C$_2$H$_2$ emission peaks in a few localized clumps where gas-phase CO$_2$ emission was previously detected with Spitzer. The distribution of excitation temperatures, derived from fits to the C$_2$H$_2$ line profiles, ranges from 50 to 200 K, which is consistent with that derived for gaseous CO$_2$—suggesting that both molecules probe the same warm gas component. The C$_2$H$_2$ molecules are excited via radiative pumping by 13.7 $\mu$m continuum photons emanating from the HW2 protostellar region. We derive column densities ranging from a few $\times 10^{13}$ to $7 \times 10^{14}$ cm$^{-2}$, corresponding to C$_2$H$_2$ abundances of $1 \times 10^{-9}$ to $4 \times 10^{-8}$ with respect to H$_2$. The spatial distribution of the C$_2$H$_2$ emission and a roughly constant $N$(C$_2$H$_2$)/$N$(CO$_2$) strongly suggest an association with shock activity, most likely the result of the sputtering of acetylene in icy grain mantles.

Subject headings: ISM: individual (Cepheus A East) — ISM: jets and outflows — ISM: molecules

1. INTRODUCTION

Acetylene constitutes a key ingredient in the production of large complex hydrocarbon molecules in the dense interstellar medium (Herbst 1995). Because acetylene has no permanent dipole moment, it lacks a rotational spectrum that could be observed at radio wavelengths; observations of interstellar acetylene have therefore been limited to mid-infrared studies of rovibrational bands, carried out from ground-based (e.g., Evans et al. 1991; Carr et al. 1995) and space-based (e.g., Lahuis & van Dishoeck 2000; Boonman et al. 2003; Lahuis et al. 2007) observatories. Acetylene has been detected in the gas-phase—either in absorption (e.g., Carr et al. 1995; Lahuis & van Dishoeck 2000) or in emission (e.g., Boonman et al. 2003; this Letter)—mostly toward young stellar objects. C$_2$H$_2$ can be used as a tracer of warm (100–1000 K) molecular gas along often complicated sight lines. C$_2$H$_2$ abundance estimates, which were sometimes a few orders of magnitude higher than the predictions of cold gas-phase steady state chemical models, have led to a better understanding of the role that warm gas-phase chemistry (e.g., Doty et al. 2002; Rodgers & Charnley 2001) and/or grain mantle processing (e.g., Ruffle & Herbst 2000) can play in star-forming regions, both locally and in extragalactic objects (Lahuis et al. 2007).

In this Letter, we present the first detection of the $\nu_3$ band of acetylene (C$_2$H$_2$) at 13.7 $\mu$m toward the star-forming region Cepheus A East, using the Infrared Spectrograph (IRS) on board the Spitzer Space Telescope. This is the first map of C$_2$H$_2$ obtained toward any interstellar gas cloud. In § 2 we describe the observations and data analysis. In §§ 3 and 4 we compare the spatial distribution of C$_2$H$_2$ with those of gaseous CO$_2$ and H$_2$ S(2), and we discuss the C$_2$H$_2$-emitting gas in the context of shock chemistry and local outflow activity. The presence of C$_2$H$_2$ on interstellar dust grains will also be discussed in the context of cometary-ice composition.

2. OBSERVATIONS AND DATA ANALYSIS

Spectral maps were obtained with the IRS on board Spitzer as part of the Guaranteed Time Observer program 113; $1' \times 1'$ square fields were observed with the Short-Low (SL), Short-High (SH), and Long-High (LH) modules, providing wavelength coverage from 5.2 to 25 $\mu$m. We obtained continuous spatial sampling by stepping the slit perpendicular and parallel to its long axis in steps of 1/2 its width and 4/5 its length, respectively. The data were processed with version 12 of the pipeline. We used the Spectroscopy Modeling Analysis and Reduction Tool (SMART; Higdon et al. 2004), along with locally developed routines (Neufeld et al. 2006), to extract wavelength- and flux-calibrated spectra and to generate spectral line intensity maps.

To estimate the uncertainties in the C$_2$H$_2$ line intensities ($\nu_3$ band at 13.7 $\mu$m), we first calculated the standard deviation ($\sigma$) around our best fit to the local continuum for each point in the map. We then shifted the best-fit continuum by $\pm 1 \sigma$ and generated the corresponding new estimates of the line intensities. The difference between the best-fit line intensities and the intensities obtained by shifting the best-fit continuum model constitutes our $\pm 1 \sigma$ errors. Although extinction due to the long-wavelength wing of the silicate feature (9.7 $\mu$m) certainly occurs, corrections to the C$_2$H$_2$ line intensities were not applied. As we will see below, C$_2$H$_2$ arises in a warm component located mostly in front of the cold quiescent gas traced by the silicates (Sonnentrucker et al. 2008), making a direct estimate of the fraction of dust located in this warm component nearly impossible. Since our study also indicates that the silicates exhibit a homogeneous distribution over the spatial extent of the gaseous C$_2$H$_2$ emission, we are confident that the C$_2$H$_2$ intensity variations that we see are not predominantly due to extinction effects.

3. RESULTS

Figure 1 (upper panel) shows a summed IRS spectrum in the wavelength range that contains acetylene at the spatial location corresponding to one peak in the C$_2$H$_2$ line emission intensity map (HW5/6 in Fig. 2). Note that frequent order mismatches around 14 $\mu$m preclude any reliable detection of the HCN $\nu_3$ band at 14.05 $\mu$m with our data. The striking similarities between the C$_2$H$_2$ maps presented here (Fig. 2) and the gaseous CO$_2$ maps that we found previously (Sonnentrucker et al. 2006) strongly suggest that
FIG. 1.—Upper panel: Summed IRS spectrum of C$_2$H$_2$ emission toward Cepheus A East. The individual spectra were summed over a ∼6′ × 8′ region centered on the radio continuum sources’ HW5/6 positions, shown in Fig. 2. Note that the emission appearing around 14.05 μm cannot reliably be attributed to HCN because of a mismatch between the spectral orders containing the C$_2$H$_2$ and CO$_2$ emissions around this wavelength. Lower panel: Continuum-subtracted summed spectrum at the HW5/6 positions. Superposed is the calculated C$_2$H$_2$-band spectrum for $T = 50, 100, 200, \text{and} 600 \text{K}$. Note the progressive shift of the band head and $Q$-branch broadening with increasing temperature.

C$_2$H$_2$ arises in the same warm postshock gas component exhibiting gaseous CO$_2$. Because the C$_2$H$_2$ emission lines are weaker by a factor ∼10 than those of CO$_2$, we first searched for the spatial positions where C$_2$H$_2$ was detected at a >1.5 $\sigma$ level; 38 such individual spatial positions fulfilled this criterion over the mapped region shown in Figure 2. These are the spectra that we will consider when comparing the C$_2$H$_2$ distribution with that of gas-phase CO$_2$ and H$_2$S (2), a tracer of shock activity (see Fig. 3).

We constrained the gas temperature in the selected C$_2$H$_2$-emitting region, by comparing synthetic profiles of the $v_5$ acetylene band for temperatures ranging from 50 to 900 K with the observed

FIG. 2.—Upper panel: Intensity distribution of gas-phase C$_2$H$_2$. Lower panel: Column density distribution of gas-phase C$_2$H$_2$. The coordinates are offsets in arcseconds in right ascension and declination with respect to HW2 (J2000.0: $\alpha = 22^h 56^m 17.9^s$ and $\delta = +62\degr 01\arcmin 49\arcsec$; Hughes & Wouterloot, 1984), the powering source of the outflow oriented northeast from HW2 (e.g., Goetz et al. 1998). The gray contours show the distribution of NH$_3$ (1, 1) (Torrelles et al. 1993), a tracer of quiescent molecular gas. The lowest contours are 10 and 25 in steps of 25 mJy km s$^{-1}$ beam$^{-1}$. The crosses indicate the positions of other known radio continuum sources (Hughes & Wouterloot 1984) and NE denotes the edge of the outflow oriented northeast from HW2.
C$_2$H$_2$ Q-branch (13.71 $\mu$m) profile. We find that temperatures between 50 and 200 K best fit the 38 selected C$_2$H$_2$ line profiles (Fig. 1, lower panel). Note that significantly higher temperatures, such as those found by Lahuis & van Dishoeck (2000) toward other massive young stellar objects (300–1000 K), are ruled out in Cepheus A East. Most importantly, our moderate 50–200 K range coincides with the temperature range found for gaseous CO$_2$ in that same region (Sonnentrucker et al. 2006), in favor of a common spatial origin for the two species.

To estimate the column density associated with the C$_2$H$_2$ emission, the dominant excitation mechanism needs to be identified. To our knowledge, accurate collisional rates for vibrational excitation of acetylene are not available. If the collisional rates for C$_2$H$_2$ vibrational excitation were similar to those of CO$_2$ (Boonman et al. 2003), densities higher than 10$^8$ cm$^{-3}$ would be required to account for the observed emission. However, such a high density would give rise to strong high-lying H$_2$O rotational lines that are not detected (e.g., van den Ancker et al. 2000). In addition, considering the low temperature in the C$_2$H$_2$-emitting gas component relative to the energy of the $v_3 = 1$ state (E/k = 1050 K), as well as the rather low local hydrogen density inferred over this region ($n_H \approx \text{a few} \times 10^3$ to a few $\times 10^5$ cm$^{-3}$; Codella et al. 2005), it is quite unlikely that collisions are the dominant excitation mechanism. Radiative pumping by 13.7 $\mu$m continuum photons produced by warm dust local to C$_2$H$_2$ is also unlikely to produce the observed emission, because we previously determined that the radiation field in this region is dominated by dust close to the HW2 protostellar region (Sonnentrucker et al. 2006). Therefore, we conclude that radiative pumping by 13.7 $\mu$m continuum photons emanating from the HW2 protostellar region seems the most likely excitation mechanism for the observed acetylene molecules, as we also found for CO$_2$ (Sonnentrucker et al. 2006).

We computed the C$_2$H$_2$ column densities over the mapped region, following the prescription described in Sonnentrucker et al. (2006). Under these assumptions, the derived $N$(C$_2$H$_2$) values are proportional to the acetylene intensities and to the square of the angular separation from the exciting source, HW2 (e.g., González-Alfonso et al. 2002). Figure 2 displays the intensity map (upper panel) and the derived column density map (lower panel) for C$_2$H$_2$ toward Cepheus A East. The gray contours show the distribution of NH$_3$ (1, 1) as a tracer of cold quiescent molecular gas (Torrelles et al. 1993) toward the region fully sampled by ISO (2006). Under these assumptions, the derived column density map shows that both species arise from the same warm shocked component.

We finally searched for correlations between the acetylene measurements and those obtained for gas-phase CO$_2$ and H$_2$S (2), a tracer of shock activity, for those 38 positions where C$_2$H$_2$ was detected at a >1.5 $\sigma$ level. Figure 3 compares the C$_2$H$_2$ intensity with that of gaseous CO$_2$ (upper panel), as well as the C$_2$H$_2$ column density with the CO$_2$ column density (middle) and the H$_2$S(2) intensity (lower panel). In all cases, the good correlation found between acetylene, gaseous CO$_2$, and H$_2$S(2) indicates that C$_2$H$_2$ does indeed arise in the warm shocked component that also contains gaseous CO$_2$.

4. DISCUSSION

Acetylene was previously observed toward low- to high-mass star-forming regions, either in absorption (e.g., Lahuis & van Dishoeck 2000) or in emission (e.g., Boonman et al. 2003), using the Infrared Space Observatory (ISO). Excitation temperatures ranging from 10$^4$ to 900 K and abundances with respect to H$_2$ ranging from a few $\times 10^{-8}$ to a few $\times 10^{-7}$ were derived. Steady state models
of gas-phase chemistry in cold (10–50 K) dense (10^3–10^5 cm⁻³) molecular clouds predict abundances for acetylene between a few × 10⁻¹⁰ and 1 × 10⁻⁸ with respect to H₂, depending on the role that neutral-neutral destruction reactions may play (Bettens et al. 1995; Lee et al. 1996). Similar abundances are predicted by models of gas-grain chemistry in quiescent clouds, with the highest values obtained only after 10⁴ yr (Ruffle & Herbst 2000). Although such models could account for the observed abundances in the cold gas, they were unable to reproduce the enhancements observed toward the much warmer gas components in those objects. Mechanisms such as C₂H₂ ice sublimation from grain mantles and/or C₂H₂ enhancements via warm gas-phase chemistry were then invoked (e.g., Carr et al. 1995; Doty et al. 2002; Boonman et al. 2003).

For the northeast outflow region in Cepheus A East, we derive C₂H₂/H₂ abundance ratios in the range 1 × 10⁻⁹ to 4 × 10⁻⁸, for an assumed H₂ column density of 1.5 × 10^{22} cm⁻² (Gómez et al. 1999). These values are averages along the observed sight lines. The highest abundances are localized around and toward the south of the northeast position, as well as around the positions of theHW5/6 sources (see Fig. 2). This is precisely where the interaction between the northeast outflow and the ambient molecular clouds occurs, and it is in these regions that we observe strong H₂S(2) emission, a tracer of warm shocked gas. Thus, the spatial variation of the C₂H₂ abundance again strongly suggests an association with shock activity, perhaps as a result of (1) production in the gas phase via high-temperature reactions or (2) grain mantle sputtering.

Models for chemistry in hot cores (Rodgers & Charnley 2001; Doty et al. 2002) indicate that enhanced abundances of C₂H₂ (~a few × 10⁻⁸) are expected in warm regions with T ≥ 200 K. The good correlations between H₂S(2), gaseous CO₂, and C₂H₂ indicate that such high temperatures were reached in the warm gas at the passage of the nondissociative shock. However, the chemical pathways leading to the production of C₂H₂ are slow, and enhanced abundances only occur after ~10⁴ yr, a timescale much greater than that expected for shock heating of the gas (~300 yr; e.g., Kaufman & Neufeld 1996). Hence, enhanced production of C₂H₂ by high-temperature gas-phase chemistry is unlikely to be predominant in the observed region. Thus, the correlations shown in Figure 3 argue in favor of grain mantle sputtering over gas-phase production as the origin of the C₂H₂ in Cepheus A East. This is the same production mechanism that we favored for gaseous CO₂ (Sonnentrucker et al. 2006). Although, to our knowledge, models for the production of C₂H₂ in shocks are not available, our results further suggest that both C₂H₂ and CO₂ are released into the gas phase under very similar physical conditions.

The gaseous C₂H₂/CO₂ ratio is roughly constant, with a mean value of 0.08 for all sight lines where we detected acetylene at the 1.5 σ level. If this value reflects the composition of the grain mantle, and given a N(CO₂)₂/N(H₂O) ice ratio in source of 0.22 (Sonnentrucker et al. 2008), then the required N(C₂H₂) ice/N(H₂O) ice ratio is 0.02. This value is at least a factor 4 larger than those derived toward other star-forming regions (0.1%–0.5%; Evans et al. 1991; Lahuis & van Dishoeck 2000), and than those predicted by theoretical models (0.1%–0.5%; Hasegawa & Herbst 1993; Ruffle & Herbst 2000), and is at least a factor 2 larger than the gaseous C₂H₂/H₂O ratios obtained in observations of cometary comae (0.1%–0.9%; Brooke et al. 1996; Weaver et al. 1999). We speculate that these discrepancies might result from (1) the destruction of CO₂ by reaction with atomic hydrogen in shocks faster than ~30 km s⁻¹ (predicted by Charnley & Kaufman 2000) and/or (2) a greater efficiency for sputtering of C₂H₂ in slow shocks. In either case, the gaseous C₂H₂/CO₂ ratios that we observed may exceed the solid C₂H₂/CO₂ ratio, and the N(C₂H₂)/N(H₂O) ice ratio could be less than 0.02. Unfortunately, direct measurements of acetylene ice are not possible, the weak features expected from solid C₂H₂ being blurred with much stronger features of CO and H₂O (Boudin et al. 1998). However, further observations of gaseous C₂H₂ at a higher signal-to-noise ratio would be very valuable as a probe of any variations in the C₂H₂/CO₂ ratio that might provide us with important clues to the shock physics.

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Facility: Spitzer (IRS).

Although both these effects would be strongly dependent on the shock velocity, the relative constancy of the C₂H₂/CO₂ would not necessarily require any fine-tuning of the shock velocity. In reality, any sight line typically samples an ensemble of shocks with a range of shock velocities, and the constancy of the C₂H₂/CO₂ would simply indicate that the admixture of shock velocities varies little from one sight line to another (e.g., Neufeld et al. 2006).

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