MOLECULAR EXCITATION AND DIFFERENTIAL GAS-PHASE DEPLETIONS IN THE IC 5146 DARK CLOUD

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ABSTRACT

We present a combined near-infrared and molecular line study of a 25′ × 8′ area in the northern streamer of the IC 5146 cloud. Using the technique pioneered by Lada and coworkers, we construct a Gaussian-smoothed map of the infrared extinction with the same resolution as the molecular line observations in order to examine correlations of integrated intensities and molecular abundances with extinction for C18O, C18S, and N2H+. We find that over a visual extinction range of 0–40 mag, there is good evidence for the presence of differential gas-phase depletions in the densest portions of IC 5146. Both CO and CS exhibit a statistically significant (factor of ~3) abundance reduction near AV ~ 12 mag, while, in direct contrast, at the highest extinctions (AV > 10 mag), N2H+ appears relatively undepleted. Moreover, for AV < 4 mag, there exists little or no N2H+. This pattern of depletions is consistent with the predictions of chemical theory. Through the use of a time- and depth-dependent chemical model, we show that the near-uniform or rising N2H+ abundance with extinction is a direct result of a reduction in its destruction rate at high extinction because of the predicted and observed depletion of CO molecules. The observed abundance threshold for N2H+, AV ~ 4 mag, is examined in the context of this same model, and we demonstrate how this technique can be used to test the predictions of depth-dependent chemical models. Finally, we find that cloud density gradients can have a significant effect on the excitation and detectability of high dipole moment molecules, which are typically far from local thermodynamic equilibrium. Density gradients also cause chemical changes since reaction rates and depletion timescales are density-dependent. Accounting for such density/excitation gradients is crucial to a correct determination and proper interpretation of molecular abundances.

Subject headings: dust, extinction — ISM: abundances — ISM: clouds — ISM: individual (IC 5146) — ISM: molecules — stars: formation

On-line material: color figures

1. INTRODUCTION

The determination of masses, densities, energetics, and chemistry for cold molecular cores is of fundamental importance for our understanding of how and why stars form. Unfortunately, the dominant molecule in interstellar molecular clouds, H2, is generally unobservable at the low temperatures associated with star-forming cores. Consequently, the most fundamental properties of molecular clouds (and the embedded star-forming cores) have been determined almost exclusively from observations of rarer trace molecules (and their isotopes) such as CO, CS, and NH3. However, these secondary molecular tracers have been calibrated only in a handful of sources, and because of variations in chemical abundances, chemical evolution, and excitation conditions, application to other sources is inherently uncertain, making the accurate determination of important physical properties (e.g., sizes, masses, and energetics) of molecular clouds not always easy or possible.

Because of the apparent constancy of the gas-to-dust ratio in molecular clouds (Jenkins & Savage 1974; Bohlin, Savage, & Drake 1978), the most direct method of tracing the hydrogen content of a molecular cloud is to determine the distribution of dust throughout the cloud. In principle, the distribution of the dust can be derived from far-infrared and millimeter-wavelength dust emission, but the grain opacity at high densities is poorly constrained, limiting the accuracy of the dust (and hence, H2) column density determination (Kramer et al. 1998). Recently, Lada et al. (1994) developed a powerful technique for mapping the large-scale distribution of dust using multiwavelength near-infrared imaging. By measuring the near-infrared color excess of stars behind a cloud, the line-of-sight dust extinction (and hence, the total column density) can be directly determined. The technique allows measurements of the dust distribution over a significant range of angular scales and extinction (Ciardi et al. 1998; Lada, Alves, & Lada 1999, hereafter LAL99). Because the near-infrared extinction law does not vary significantly with grain growth in cold cores (Mathis 1990), the high extinction observed toward cloud cores can be anchored to the well-calibrated H2-to-dust ratio at lower extinction.

When the near-infrared excess data is combined with molecular gas emission-line observations, direct determination of the molecular abundances relative to H2 can be obtained, thus allowing a more accurate determination of the physical and chemical properties of molecular clouds and their embedded cores (Alves, Lada, & Lada 1999). Indeed, 12C18O, a molecule often assumed to trace accurately the distribution of material in cold cores, has been found to show evidence for a reduction in abundance at high extinction, which has been attributed to the freezing of gas-phase CO onto the surfaces of cold dust grains (i.e.,
depletion) in the cores of IC 5146 (Kramer et al. 1999) and L977 (Alves et al. 1999).

Kramer et al. (1999) found compelling evidence for depletion of CO onto dust grains in a cold core located in the IC 5146 dark cloud. The finding was based primarily on the relationship between the integrated intensity of $^{13}$C$\text{O}$ and the visual extinction derived from near-infrared color excess measurements. The $^{13}$C$\text{O}$ integrated intensity was found to be well correlated with $A_V$ for $A_V \leq 10$ mag. For $A_V > 10$ mag, the relationship flattens out, and the $^{13}$C$\text{O}$ integrated intensity is nearly constant out to a visual extinction of $A_V \sim 30$ mag. $^{13}$C$\text{O}$ was used to check for opacity effects, and the $^{13}$C$\text{O}$ was found to be optically thin throughout the region. Kramer et al. (1999) concluded that the most likely explanation was the depletion of CO onto the surface of dust grains. Thus, masses and densities of cold dark cores in IC 5146 derived from $^{13}$C$\text{O}$ may underestimate the true mass and densities by as much as 30%.

However, the study by Kramer et al. (1999) covered a very small region (3.3 $\times$ 3.3) and was limited to a single core in the IC 5146 dark cloud. In this paper, we present a more detailed study of the molecular gas abundances over a much larger region in the IC 5146 dark cloud (25' $\times$ 8') at moderate resolution (50'). Our primary goal is to perform, for a variety of molecular species, a direct comparison of the molecular emission and the line-of-sight dust column density in the dark cloud associated with the young cluster IC 5146. By using the line-of-sight extinction to trace the H$_2$ column density and comparing that to the measured molecular emission, a better understanding of the chemical abundances and evolution within dark molecular cores can be achieved. Since rarer trace molecules are routinely used to discern the distribution of molecular material in star-forming clouds, understanding the abundance and chemistry of these molecules is vital to our understanding of star formation.

We have obtained new radio observations of the rotational transitions of $^{12}$C$\text{O}$, $^{13}$C$\text{O}$, $^{12}$C$\text{S}$, $^{12}$C$\text{C}_2$S, $^{13}$C$\text{C}_2$S, and N$_2$H$^+$ toward the northern streamer in the dark cloud (B168) associated with IC 5146. Using the near-infrared extinction data of the same region published by LAL99, we present a detailed analysis of the correlation between the molecular gas and the dust column density in the IC 5146 dark cloud. In §2 of this paper we describe the near-infrared data utilized in this study. In §3 we describe the acquisition and reduction of the radio molecular line observations. In §4 we examine the excitation and present molecular abundance profiles against extinction. In §5 we discuss the implications of these observations, and in §6 we detail our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Near-Infrared Extinction

The near-infrared data used in this paper are taken from LAL99, in which a detailed description of the data acquisition, reduction, and source extractions may be found. The area surveyed is approximately 27' $\times$ 8', and the photometry is complete (at the 10 σ level) to a depth of $H \approx 17$ and $K \approx 16$ mag. The infrared color excess for each star was determined via $E(H - K) = (H - K)_{\text{obs}} - (H - K)_{\text{local}}$, where $(H - K)_{\text{local}} = 0.13 \pm 0.01$ mag, which is the mean color of field stars observed in a nearby, unextincted control field (Lada et al. 1994; LAL99). The color excess for each star was converted to an extinction using the reddening law of Reike & Lebofsky (1985): $A_K = 1.78E(H - K)$ and $A_V = 15.9E(H - K)$.

The extinction derived in this manner is directly proportional to the true dust column density along that line of sight under the assumption that the H$_2$-to-dust ratio remains constant. The conversion of the measured near-infrared color excess to the conventional visual extinction may not truly represent the actual visual reddening of a background star because grain growth in cold clouds alters the extinction law at $\lambda < 1$ µm. However, at near-infrared wavelengths, the reddening law is not known to vary significantly with grain growth (see, e.g., Mathis 1990), and the derived near-infrared extinctions remain proportional to the line-of-sight column density. Moreover, the conversion of the measured infrared extinction to the conventional visual extinction maintains the proportionality. The use of $A_K$ instead of $A_V$ would avoid this confusion, but to facilitate comparison to other work (e.g., Lada et al. 1994; Ciardi et al. 1998; Alves et al. 1998; Kramer et al. 1999; LAL99), we report visual extinction throughout this paper.

To enable a direct comparison between the near-infrared observations and the radio molecular line observations (obtained with the FCRAO telescope and described in the next section), the mean near-infrared extinction along each line of sight associated with a molecular line observation is calculated by convolving the individual infrared excess measurements with a two-dimensional Gaussian filter. The Gaussian filter has a FWHM of 50'' to match the approximate beam size of the FCRAO telescope and is truncated at $r = 3 \sigma$. The uncertainty on the mean extinction is estimated from the Gaussian-weighted rms dispersion of extinction measurements falling within each "beam." The Gaussian-convolved map of visual extinction is shown in Figure 1a. This map is quite similar to the larger extinction map of IC 5146 presented by LAL99.

2.2. Molecular Line Observations

Over two separate observing periods (1999 March 23–25 and 2000 January 31–February 1), the 14 m telescope at the FCRAO in New Salem, Massachusetts, was used to observe a 25' $\times$ 8' region covering the northern streamer of the IC 5146 dark cloud. The rotational transitions of the following molecules were observed: $^{12}$C$\text{O}$ (109.782182 GHz, $J = 1 \rightarrow 0$, hereafter C$\text{O}$), the hyperfine triplet of $^{13}$C$\text{O}$ (112.359277 GHz, $J = 1 \rightarrow 0$, hereafter C$\text{O}$—note that the two reddest components are blended and unresolved at our spectral resolution of 78 kHz; see below), $^{12}$C$\text{S}$ (97.981011 GHz, $J = 2 \rightarrow 1$, hereafter CS), $^{12}$C$\text{S}$ (96.412962 GHz, $J = 2 \rightarrow 1$, hereafter CS), $^{13}$C$\text{S}$ (92.4979 GHz, $J = 2 \rightarrow 1$, hereafter CS), and N$_2$H$^+$ (93.173777 GHz, $J = 1 \rightarrow 0$). The N$_2$H$^+$ transition consists of seven hyperfine components spanning 4.7 MHz; however, at our spectral resolution (78 kHz; see below), only the three main groups of lines centered at rest frequencies of 93.1719 (a blend of three lines), 93.1738 (a blend of three lines), and 93.1763 GHz (a single line) are resolved (see, e.g., Caselli, Myers, & Thaddeus 1995).

The observations reported in this paper were obtained with the newly commissioned SEQUOIA 16-element focal-plane array receiver. The 16 elements of the SEQUOIA array are aligned in a square 4 $\times$ 4 pattern; each element is separated from its neighbor by 88" in both the X- and Y-directions. A full-beam–sampled map requires four
pointings of the array on the sky and is referred to as a "footprint." All maps were centered with respect to \( \alpha(J2000) = 21^h 47^m 27^s \) and \( \delta(J2000) = 47^\circ 31^\prime 00^\prime\). The FAAS autocorrelator spectrometer was utilized in the 512 channel, 40 MHz bandwidth mode, yielding a channel spacing of 78 kHz (\( \Delta v \sim 0.21 \text{ km s}^{-1} \) at 112 GHz and \( \Delta v \sim 0.25 \text{ km s}^{-1} \) at 93 GHz). The 1999 data were taken in position-switching mode, while the 2000 data were taken in frequency-switching mode. For the frequency-switched data, the signal frequency was shifted by 4 MHz. Typical system temperatures ranged from 140 to 300 K. The integrations times for each molecule varied (see Table 1), but typical rms noise temperatures per channel were \( \lesssim 0.02 \text{ K} \). Internal calibration was done via a chopper wheel that allows switching between the sky and an ambient temperature load. The focusing and pointing were checked by observing periodically the SiO masers T Cep (1999) and R Cas (2000). Typically, rms pointing uncertainties were 5\'.

The northern streamer was mapped at full-beam sampling in C\(^{18}\)O, CS, and N\(_2\)H\(^+\). The 25\' \( \times \) 8\' map was rotated by 14\' north of east with respect to equatorial coordinates to follow the long axis of the cloud and the near-infrared survey data (see, e.g., Lada et al. 1994; LAL99). The full map required four footprints for a total of 256 grid points. The streamer contains two dense cores, which are readily detectable in a 50\' beam and were mapped at full-beam sampling in C\(^{18}\)S. The positions of the grid points in these two individual footprints are no different than the positions found in the full map. A single additional footprint (64 grid points) was observed toward the eastern core in C\(^{18}\)O. This footprint was offset from the regular map grid by \(-0.369\) \( \sim 0.5 \) beam size) in both right ascension and declination. The purpose of this footprint was to increase the sampling of the C\(^{18}\)O in the eastern core. Additional single-array placements (16 grid points) on the eastern core were observed in C\(^{18}\)O, C\(^{17}\)O, and \(^{13}\)CS. These single-array observations were used to investigate the C\(^{18}\)O and CS optical depth of the core (see \$3.1 and 3.2).

A summary of the map grid points is shown in Figure 1, and details of the observing parameters for each molecular observation can be found in Table 1. Several points on the southeastern edge of the radio grid fall outside of the infrared survey region, and these data points are not included in this study.
For the remainder of the paper, the “eastern core” refers to the easternmost footprint (i.e., the easternmost 8 × 8 grid), the “western core” refers to the westernmost footprint (i.e., the westernmost 8 × 8 grid), and the “midstreamer” refers to the two footprints (16 × 8 grid) lying between the eastern and western cores (see Fig. 1).

All data were reduced using SPA and CLASS spectral line reduction packages in conjunction with custom-made analysis routines. A second-order polynomial baseline was subtracted from the position switch spectra; the frequency-switched spectra were folded, and a second-order polynomial baseline was subtracted. Main-beam efficiencies of \( \eta_{MB} \approx 0.50-0.55 \) were adopted from the SEQUOIA documentation. Final \( T_R \) rms noise temperatures were generally \( \lesssim 0.04 \) K. All data presented in the paper are corrected using the main-beam efficiency and are on the \( T_R \) scale.

3. RESULTS: COMPARISON OF THE DUST AND GAS

Figures 2a and 2b present maps of the integrated emission of \(^{18}\)O and \(\text{N}_2\text{H}^+\) in IC 5146. The map of the \(^{18}\)O \( J = 1 \rightarrow 0 \) integrated intensity appears broadly similar in distribution to the visual extinction map shown in Figure 1. Both extinction and \(^{18}\)O trace column density enhancements, or cores, at the eastern and western edges of the mapped region, although the \(^{18}\)O emission peaks are slightly offset from those of \( A_V \). The integrated emission of \(\text{N}_2\text{H}^+\) shows strong emission toward the eastern core and only weak and somewhat clumpy distribution throughout the rest of the streamer. Curiously, the \(\text{N}_2\text{H}^+\) intensity appears to correlate reasonably well with the regions of highest extinction. This is more clearly demonstrated in Figure 3, in which the integrated intensity distribution of \(\text{N}_2\text{H}^+\) and \(^{18}\)O are compared with visual extinction in the western core. Here the strongest \(\text{N}_2\text{H}^+\) emission appears directly on the peak of extinction, while the \(^{18}\)O emission maxima are offset by nearly 1'. This is unlikely to be the result of differences in excitation requirements between these two transitions. The upper-state energy of each transition is \( \sim 5 \) K, and, while \(\text{N}_2\text{H}^+\) has a large critical density (\( \sim 10^5 \text{ cm}^{-3} \)) and preferentially samples only the highest densities, the \(^{18}\)O emission should also trace the same density regimes. Instead, these morphological differences are likely due to differences in the chemistry, as will be discussed later in this paper.

Figure 4 presents the total integrated emission for the \( J = 2 \rightarrow 1 \) transitions of CS and \(^{34}\)S. The CS emission morphology is similar to that of \(^{18}\)O since CS strongly peaks on both cores and shows weak, but detectable, emission from the gas between the cores. Because of its weaker intensity, the \( J = 2 \rightarrow 1 \) transition of \(^{34}\)S was only observed in the two cores. Within these smaller regions, the \(^{34}\)S emission is roughly similar to that of its more abundant isotope, CS.

In Figure 5 selected spectra at two different positions are presented. The two chosen positions are (\( \Delta x = +0.2, \Delta \delta = +0.7 \)) and (\( \Delta x = -0.9, \Delta \delta = +2.5 \)) and both are associated with the eastern core and sample extinctions that differ by a factor of 2. Here we see that the intensity of \(^{17}\)O is significantly lower at the highest extinction (for \( A_V = 36 \) mag, the detection is \( 16 \sigma \) on the integrated intensity, while at \( A_V = 19 \) mag, the detection is \( 4 \sigma \)). In contrast, the emission of \(^{34}\)S and \(\text{N}_2\text{H}^+\) appears to be stronger at the position with higher extinction. These differences, shown at only two positions, will be examined in greater detail with higher sampling in the following sections.

3.1. \(^{18}\)O

The direct comparison between the \(^{18}\)O integrated intensity and visual extinction at each point in the mapping grid is presented in Figure 6. The behavior of these two tracers is very similar to what was found previously for the IC 5146 region (Lada et al. 1994; Kramer et al. 1999). The integrated intensity and the extinction appear well correlated for \( A_V \leq 10-15 \) mag. For \( A_V \geq 10-15 \) mag, the relationship shows a high degree of scatter and appears to flatten out.

A bivariate linear fit was performed for the data located at \( A_V < 10 \) mag, with the following result:

\[
I(\text{^{18}O}) = (-0.4 \pm 0.1 \text{ K km s}^{-1}) + [0.20 \pm 0.01(\text{K km s}^{-1}) \text{mag}^{-1}]A_V. \tag{1}
\]

The above fit is in excellent agreement with the fit presented by LAL99 for a similar region but at lower angular resolution (102') than the observations presented here.
fit is also in agreement with the $^{18}$O-$A_V$ relationship found for the smaller region (and finer beam size: 30") studied by Kramer et al. (1999). However, if the entire extinction range is used in the fit, the resulting slope is 15% shallower, which is consistent with earlier findings for both IC 5146 (Lada et al. 1994) and also in L977 (Alves et al. 1999).

The two most likely effects that could explain the change in slope at high extinction are (1) high $^{18}$O optical depth for $A_V \gtrsim 10$ mag and (2) depletion of CO onto the surface of dust grains. A third possibility is a decrease of the CO excitation temperature to $T_{ex} \lesssim 5$ K for $A_V \gtrsim 10$ mag. However, Alves et al. (1999) for a similar result in L977 make a convincing argument that this is not a likely possibility. They argue that heating mechanisms (cosmic-ray rates, ambipolar diffusion, and natural radioactivity) are sufficient to prevent the gas in cloud cores to cool below 5 K. Although we cannot completely rule out this possibility, we regard the cooling of the gas to such extreme temperature as unlikely and proceed with a discussion of the optical depth and depletion.

The paired $^{18}$O-$^{17}$O single-pointing observations provide information regarding the optical depth of the $^{18}$O in the densest portions of the eastern core (see Table 1). $^{18}$O and $^{17}$O should be collisionally excited under the same physical conditions deep inside cold cores where the molecules are well shielded from external ultraviolet radiation (Ladd, Fuller, & Deane 1998; van Dishoeck & Black 1988). Additionally, the ratio $[^{18}$O]/$[^{17}$O] = 3.65 ± 0.15 appears to be relatively constant throughout the interstellar medium (Penzias 1981). Thus, the only difference in the emission between $^{18}$O and $^{17}$O should arise from the oxygen relative abundance; i.e., completely optically thin emission of $^{18}$O and $^{17}$O should have an integrated intensity ratio of 3.65.

A comparison of the integrated intensities of $^{17}$O versus $^{18}$O is shown in Figure 7 (top panel). The solid line represents the expected ratio of 3.65 for optically thin emission and does not represent a best fit to the data. The dashed lines represent the 1 $\sigma = \pm 0.15$ uncertainty of the $[^{18}$O]/$[^{17}$O] ratio. The excellent agreement of the data distribution with the predicted ratio indicates that the $^{18}$O emission is indeed optically thin.

To test directly for optical depth effects as a function of total column density, the $^{18}$O/$^{17}$O ratio has been plotted as a function of extinction (bottom panel of Fig. 7). The extinction provides an independent assessment of the total column density along each line of sight. If the $^{18}$O was optically thick at a high column density (high extinction),
the C\textsuperscript{18}O/C\textsuperscript{17}O ratio should systematically decrease as a function of increasing extinction. The ratio is remarkably constant over a range of 40 mag of visual extinction. Figure 7 implies that (1) the [\textsuperscript{18}O]/[\textsuperscript{17}O] ratio in IC 5146 is very near the previously determined interstellar value of 3.65 ± 0.15, and (2) that the C\textsuperscript{18}O emission is not highly optically thick. However, because of the errors in the ratios, we cannot rule out the C\textsuperscript{18}O emission being thin but with moderate optical depth (\(\tau \approx 0.5\)).

The ratio of the three hyperfine components of C\textsuperscript{17}O can be used to determine whether or not C\textsuperscript{17}O is thin. The relative intensities of the three components (central: blue:red) are 4:3:2 for optically thin emission (Ladd et al. 1998). At the spectral resolution of our data (78 kHz), the central and red components are blended; thus, the measured relative intensity of the two components (central red blend:blue) should be 2:1 for optically thin emission, and, indeed, the measured median relative intensity is 2 ± 0.5. If this is the case, then the difference in the two C\textsuperscript{17}O spectra presented in Figure 5, with the highest extinction having lower emission, is suggestive of a drop in abundance.

### 3.2. CS

The depletion of sulfur-bearing molecules (e.g., CS and SO) is predicted to be a sharp function of the density, and these species should be robust tracers of gas-phase molecular depletion onto the surface of dust grains in cloud cores (Bergin & Langer 1997). Since there was already evidence to suggest that CO may be depleted in the cores of IC 5146 (§ 3.1), CS should also show evidence for gas-phase depletion.

To explore this hypothesis, the C\textsuperscript{34}S optical depth was computed for both the eastern and western cores at positions where we have observations of both CS and C\textsuperscript{34}S using the following relationship:

\[
\frac{T(C\textsuperscript{34}S)}{T(CS)} = 1 - \exp(-\tau) \quad \frac{1 - \exp(-\alpha\tau)}{1 - \exp(-\tau)},
\]

where \(\tau\) is the C\textsuperscript{34}S optical depth and \(\alpha\) is the abundance ratio of [\textsuperscript{32}S]/[\textsuperscript{34}S] = 14 (Pratap et al. 1997). Using the ratio of the integrated intensities, we iteratively solved equation (2) for \(\tau\) until the calculated intensity ratio matched the measured intensity ratio to within ~5%. In Figure 8, the C\textsuperscript{34}S optical depth is shown as a function of the visual extinction \(A_V\). The uncertainties shown in Figure 8 are a result of the uncertainties in the integrated intensity measurements; the uncertainties associated with the convergence of the numerical calculations are significantly smaller. The derived opacities clearly indicate that the emission from C\textsuperscript{34}S is optically thin in both cores for all values of \(A_V\). However, the emission from CS (\(\tau_{CS} = \tau_{C\textsuperscript{34}S} 14\)) must be optically thick throughout the cloud. Surprisingly, despite being thin, the C\textsuperscript{34}S optical depth is nearly constant for \(A_V \geq 10\) mag.

As a check of the derived optical depths, the optical depth of \(^{13}\)CS was calculated in a similar manner to the C\textsuperscript{34}S optical depth. Only the position (~0.54, 0.89) was sufficiently strong to permit such a calculation.
Fig. 4.—(a) Map of CS J = 2 → 1 integrated intensity in IC 5146. Contour levels begin with 0.5 K km s$^{-1}$ and are spaced by 0.5 K km s$^{-1}$. (b) Smaller maps of the integrated C$^{34}$S J = 2 → 1 emission. Contour levels begin at 0.2 K km s$^{-1}$ and increase in steps of 0.1 K km s$^{-1}$. The stars show the positions of IRAS point sources. [See the electronic edition of the Journal for a color version of this figure.]

[$T(^{13}CS)d\nu = 0.089 \pm 0.02$ K km s$^{-1}$]. An optical depth of $\tau = 0.033 \pm 0.008$ was found, implying that the C$^{34}$S optical depth (assuming an abundance ratio of [C$^{34}$S]/[C$^{13}$S] = 4.29) is $\tau = 0.14 \pm 0.03$ (see Fig. 5). The C$^{34}$S optical depth measured using the $T(\text{C}^{34}\text{S})/T(\text{CS})$ ratio is $\tau = 0.14 \pm 0.04$ at the same position, confirming the small opacities of C$^{34}$S in this cloud.

Examining the dependence of C$^{34}$S opacity with extinction in Figure 8, we find that while the extinction rises by a factor of 2.5 (15–40 mag), the C$^{34}$S optical depth remains nearly constant at $\tau \approx 0.15$–0.25. Indeed, there is even a small hint that the optical depth of the C$^{34}$S in the eastern core is decreasing as a function of increasing extinction. The eastern core also appears to have an opacity that is, on average, slightly higher than the western core. Since optical depth is a direct tracer of column density in either the upper or lower state, this difference suggests that the abundance of CS could be different between the two cores. Moreover, the constant opacity with extinction for both cores would then be indicative of a C$^{34}$S (and CS) abundance decrease with increasing extinction. However, CS and C$^{34}$S have high dipole moments, and their emission is sensitive to gas density as opposed to C$^{18}$O emission, which is fairly insensitive to the density (provided $n_{\text{H}_2} > 1000$ cm$^{-3}$). Thus, for CS and its isotopic variants, changes in the excitation conditions can play an important, and with regards to depletion analyses, potentially confusing role. These effects are examined in § 4.

3.3. N$_2$H$^+$

Unlike CS or even CO, N$_2$H$^+$ is predicted by evolutionary chemical models to have a low depletion rate because of the relatively low binding energy of its precursor molecule, N$_2$ (Bergin & Langer 1997). Thus, we might expect that N$_2$H$^+$ would exhibit a different behavior as a function of extinction when compared to CS or CO.

In Figure 9, the N$_2$H$^+$ integrated intensity summed over all hyperfine transitions is compared to the visual extinction. This figure clearly shows quite a different relationship between N$_2$H$^+$ integrated emission and visual extinction when compared to the other species included in our study. For $A_V \lesssim 15$ mag, the N$_2$H$^+$ integrated intensity versus $A_V$ is nearly flat and follows the following relationship:

$$I(\text{N}_2\text{H}^+) = (-0.03 \pm 0.04 \text{ K km s}^{-1})$$

$$+ [0.017 \pm 0.006 \text{ (K km s}^{-1}) \text{ mag}^{-1}] A_V ;$$

$$A_V < 15 \text{ mag} .$$

(3)
Fig. 5.—Plot showing selected spectra at two different positions in the eastern core: \((\Delta x = +0.2, \Delta \delta = +0.7)\) with \(A_V = 36\) mag and \((\Delta x = -0.9, \Delta \delta = +2.5)\) with \(A_V = 19\) mag.
Fig. 6.—C\textsuperscript{18}O integrated intensity vs. visual extinction for the entire northern streamer. The best-fit linear relationship for $A_V \leq 10$ mag is given as the solid line and is extrapolated as the dot-dashed line for $A_V > 10$ mag. The median uncertainties in the measurements are shown in the lower right-hand corner. The eastern core, western core, and midstreamer are plotted as different symbols as indicated in the upper left-hand corner of the figure.

Fig. 7.—(a) Comparison of the C\textsuperscript{17}O and C\textsuperscript{18}O integrated intensities in the eastern core. The solid line represents the expected trend ($\pm 1 \sigma$; dashed lines) for optically thin emission. (b) C\textsuperscript{18}O/C\textsuperscript{17}O ratio of integrated intensities vs. visual extinction. The solid line represents the expected ratio for optically thin emission. The dashed lines represent the median $1 \sigma$ uncertainty of the measured ratios.
Fig. 8.—$^{34}$S optical depth vs. visual extinction for the eastern and western cores. The eastern and western cores are plotted as different symbols as indicated in the upper left-hand corner of the figure. The circle at $A_v \approx 27$ mag represents the optical depth as derived from the $^{13}$CS data. The $^{34}$S optical depth measured for that same line of sight overlaps the $^{13}$CS derived optical depth.

Fig. 9.—$N_2H^+$ integrated intensity vs. visual extinction for the entire northern streamer. The best-fit linear relationship for $A_v < 15$ mag is plotted as the dashed line, and the best-fit linear relationship for $A_v > 15$ mag is plotted as the solid line. The median uncertainties in the measurements are shown in the lower right-hand corner. The eastern core, western core, and midstreamer are plotted as different symbols as indicated in the upper left-hand corner of the figure.
Note that the slope of the linear fit is nonzero at the 3\(\sigma\) level, indicating that the \(N_2H^+\) intensity gradually increases with extinction. At \(A_v \geq 15\) mag, the intensity displays a sharp increase, and the \(N_2H^+-A_v\) relationship steepens by nearly a factor of 15:

\[
I(\text{N}_2\text{H}^+) = (-4.3 \pm 0.6 \text{ K km s}^{-1}) \\
+ [0.26 \pm 0.03 \text{ (K km s}^{-1}\) mag\(^{-1}\)] \\
\times [A_v] ; \\
A_v > 15\text{ mag.} \tag{4}
\]

Curiously, the increase in \(N_2H^+\) intensity occurs at a similar visual extinction to where the CO-\(A_v\) relationship begins to show evidence of potential depletion. The derivation of \(N_2H^+\) abundances and the physical cause for the sharp increase at \(A_v \geq 15\) will be discussed in the following section.

4. ANALYSIS: MOLECULAR EXCITATION AND ABUNDANCES

In the previous section we searched for correlations between integrated emission and visual extinction for each of the surveyed molecules. Here we examine whether any departures from the correlation are the result of excitation and/or abundance gradients. In this section we concentrate on trends in relative or normalized abundances (i.e., abundances normalized using the abundance derived at the lowest extinction with reliable data points). In this fashion, in the determination of molecular abundance for a given species, we eliminate common uncertainties (such as collision rates).

To calculate total column densities from the molecular data, we account for the radiation transfer through the use of the large velocity gradient (LGV) approximation. To reduce the effects of opacity, we use here only the \(^{17}\text{O}, \text{C}^{34}\text{S}, \text{and N}_2\text{H}^+\) data. Since the emission of \(^{17}\text{O}\) and \(\text{C}^{34}\text{S}\) is optically thin and, based on ratios of hyperfine components, much of the \(N_2\text{H}^+\) emission is also thin, this reduces the LGV approximation to simply solving the equations of statistical equilibrium. The results are therefore less dependent on the details of the radiative transfer solution. To improve the statistics of our results, we average abundances in bins of 5 mag starting with \(A_v = 5\) mag. Below this value, there are little or no significant (\(>3\)\(\sigma\)) data points (for \(N_2\text{H}^+, ^{17}\text{O}, \text{and C}^{34}\text{S}\)).

In this study we observe only a single transition of a given molecular species. However, in each case, we have information on the optical depth, using CS for \(\text{C}^{34}\text{S}, \text{and the hyperfine ratios for}^{17}\text{O and N}_2\text{H}^+\). This provides an additional and limiting constraint on the column density determination. With the observed intensity and opacity from a single transition, the total column density can be derived with knowledge of the collision rates, density, temperature, and line width. The collision rates are available from the literature, and the line width or velocity dispersion is an observed quantity. However, to derive a map of the total column density from the molecular line maps requires a priori knowledge of the density and temperature structure of the IC 5146 cloud.

For the density structure, we use the analysis in LAL99, who show that the extinction (or column density) gradient in the same region of IC 5146 is nicely reproduced by a cylindrical geometry (for the entire streamer) with \(\rho \propto r^{-2}\). The procedure LAL99 use to determine the density structure is identical to the commonly used method of deriving the volume density structure from millimeter and submillimeter dust continuum emission (see Shirley et al. 2000 and references therein). To be consistent with the results in LAL99, which show a large systematic increase in volume density from low to high extinction, we adopt the following density profile: \([n_{H_2} = n_H^+(r = r_0)/r]^2 = 10^5(0.047 \text{ pc}^2/r)^2 \text{ cm}^{-3}\). The density profile is shown in Figure 10 and is in reasonable agreement with the radial profile of total column density (Fig. 8 in LAL99). In our calculations, we use average densities in bins of 5 mag (shown as horizontal hash marks in Fig. 10). For example, if a given data point has an extinction between 5 and 10 mag, then we use the average density of \(n_{H_2} = 1.4 \times 10^4 \text{ cm}^{-3}\) within that bin.

There exists some information on the temperature structure from observations of CO and \(\text{NH}_3\). CO observations generally show gas temperatures ranging from 10 to 13 K (Dobashi et al. 1992). However, these estimates are likely reflective of the temperature at the cloud surface and not the denser interior (Bergin et al. 1994). In the eastern core, \(\text{NH}_3\) observations provide some information on the dense gas temperature with \(T = 13\) K (Jijina, Myers, \& Adams 1999). We also have a single detection of the \(J = 6 \rightarrow 5 (K = 0 \text{ and } 1)\) transition of \(\text{CH}_3\text{C}_2\text{H}, \text{which can be used to estimate the temperature (Bergin et al. 1994). Since this detection is at a single position} (\Delta z = -0.5, \Delta \delta = +0.9), \text{we have not shown the spectra; however, the} K = 0 \text{ integrated intensity is} \int T dv = 0.11 \pm 0.02 \text{ K km s}^{-1}\text{ and } K = 1 \text{ is} \int T dv = 0.13 \pm 0.02 \text{ K km s}^{-1}\text{ Using the method described in Pratap et al. (1997), the ratio of these two is consistent, within the errors, with a gas temperature less than 13 K. Given this information, it is unlikely that there are strong temperature gradients throughout most of the IC 5146 molecular streamer with the probable range between (perhaps) 5 and the CO temperature of 13 K. In the following discussion, we present abundances calculated with a constant temperature of 10 K and discuss the results of

![Graph showing volume density of molecular hydrogen as a function of visual extinction and radius. This profile is in good agreement with the profile of extinction with cloud radius determined in LAL99. The horizontal hash marks found along the line representing the density profile are the average densities used in the molecular abundance analysis for respective bins of 5 mag starting with \(A_v = 5\)–10 mag.](image-url)
additional analysis assuming constant temperatures of 5 and 13 K (and combinations thereof).

4.1. C\(^{17}\)O Abundance

Because of concerns that moderate opacities in C\(^{18}\)O emission could potentially mask small abundance changes in order to search for relative abundance differences, we predominantly use the more limited C\(^{17}\)O observations. For the C\(^{17}\)O column density derivation, we use the collision rates of CO with para-H\(_2\) (Flower 1988). We adopt the density determined as a function of extinction as described above, and the temperature is assumed to be constant at 10 K for each position (changes in the temperature will be discussed below). The line width is determined via Gaussian fits to each spectrum. Because the C\(^{17}\)O \(J = 1 \rightarrow 0\) transition has hyperfine structure, we use this additional information in our derivation of column density. We therefore simultaneously fitted the two resolved hyperfine components (as discussed in § 3.1, the \(F = 7/2 \rightarrow 5/2\) and \(F = 3/2 \rightarrow 5/2\) transitions are blended), assuming that the hyperfine levels are populated according to LTE. The two constraints on the on the \(\chi^2\) search for the best-fit column density are (1) the intensity of the lines and (2) the relative intensities of the hyperfine ratios, which limit the opacity of the solution. In general, the reduced \(\chi^2\) of most solutions is less than 1, and in all cases, the C\(^{17}\)O emission is found to be optically thin. For each position, we derive column densities if the observed integrated intensity is greater than 3 \(\sigma\), and in all cases, the C\(^{17}\)O abundance relative to H\(_2\) is derived using \(N_{\text{H}_2} = 10^{21}A_V\).

Table 2 presents the weighted average abundance of C\(^{17}\)O (within 5 mag bins of extinction), and in Figure 11 the relative abundance of C\(^{17}\)O is given as a function of visual extinction. In this figure we normalize the abundance to the lowest extinction bin with a statistically significant abundance determination (between 5 and 10 mag). Excluding the point at \(A_V = 27.5\) mag with large errors, we see that the relative C\(^{17}\)O abundance shows a steady and significant decrease, by a factor of 3, from the lowest to highest visual extinction. This result is found by assuming a constant temperature of 10 K. To investigate whether a systematic temperature gradient can change the result, we repeated the same procedure assuming constant temperatures of 5 and 13 K. To mimic temperature gradients, we examined combinations of these results. In the absence of a significant population of luminous embedded stars (the case here), the most likely systematic temperature gradient is the temperature decreasing with increasing extinction. In this case, we find that the C\(^{17}\)O abundance at high \(A_V\) (with \(T = 5\) K) does increase because of higher opacity in the \(J = 1\) state, allowing for greater column density, but by only 15%. At the cloud edges (provided \(T = 13\) K), the abundance also shows a slight increase, primarily because of the lower population in the \(J = 1\) state. If the temperature were even greater, then the abundance would continue to rise. In all, this examination still provides a factor of 3 decrease in the C\(^{17}\)O abundance from \(A_V = 5\) to 40 mag. It is worth emphasizing that even if CO and its isotopic variants are completely depleted in the dense core center, the molecular observations will detect emission from the relatively undepleted gas residing in the low-density regions along the line of sight through the core. Thus, if CO shows evidence for depletions at 10 mag in a cloud with a total extinction (from, e.g., Fig. 5) of 40 mag, then the measured abundance will drop by at most a factor of 4.

A similar analysis was performed using the entire C\(^{18}\)O data set, and we find that the relative abundance is essentially constant until the highest extinction bin, whereupon the abundance decreases by a factor of 1.5. This confirms our suspicion that the C\(^{18}\)O emission is likely to have moderate optical depth (\(\tau \sim 0.5\)), which masks the larger abundance difference (factor of 3) seen in C\(^{17}\)O. We note that one core in our data set (\(\Delta x = -9.2, \Delta \delta = 2.9\)) has been examined with the IRAM 30 m antenna at a higher (\(\sim 30^\circ\))

![Figure 11](image)

**Figure 11.** Normalized molecular abundances derived from combined molecular column densities and near-infrared extinction measurements of C\(^{17}\)O (circles and solid line), C\(^{34}\)S (squares and dashed line), and N\(_2\)H\(^+\) (triangles and dotted line) relative to H\(_2\), shown as a function of extinction in the visual. The data are weighted averages within bins of 5 mag; thus the errors are reflective of the total number of data points included in the average and of the percentage error of the individual data points. The abundances are normalized using the data in the first bin (\(A_V = 5\)–10 mag) in order to see the trend in relative abundances as a function of extinction.

| \(A_V\) (mag) | C\(^{17}\)O \((\times 10^{-11})\) | C\(^{34}\)S \((\times 10^{-11})\) | \(N_{\text{C}_2\text{H}_2}\) \((\times 10^{-11})\) | \(N_{\text{C}_3\text{H}_2}\) \((\times 10^{-11})\) | \(N_{\text{H}_2}\) \((\times 10^{-11})\) |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 7.5 \(\ldots\ldots\) | 0.29 \(\pm\) 0.08 | 3 | 17.0 \(\pm\) 1.7 | 12 | 12.8 \(\pm\) 1.8 | 8 |
| 12.5 \(\ldots\ldots\) | 0.27 \(\pm\) 0.04 | 5 | 9.8 \(\pm\) 0.6 | 17 | 6.7 \(\pm\) 0.6 | 18 |
| 17.5 \(\ldots\ldots\) | 0.26 \(\pm\) 0.03 | 4 | 7.9 \(\pm\) 1.0 | 3 | 4.5 \(\pm\) 0.4 | 9 |
| 22.5 \(\ldots\ldots\) | 0.20 \(\pm\) 0.05 | 3 | 6.6 \(\pm\) 0.9 | 6 | 6.4 \(\pm\) 0.7 | 8 |
| 27.5 \(\ldots\ldots\) | 0.34 \(\pm\) 0.11 | 1 | 6.8 \(\pm\) 0.9 | 3 | 11.3 \(\pm\) 1.7 | 3 |
| 32.5 \(\ldots\ldots\) | 0.09 \(\pm\) 0.02 | 1 | 5.8 \(\pm\) 0.7 | 1 | 8.8 \(\pm\) 0.9 | 1 |

**Note:** The values of \(n_{\text{C}_2\text{H}_2}\), \(n_{\text{C}_3\text{H}_2}\), and \(n_{\text{H}_2}\) are the number of points included in binned average.
resolution by Kramer et al. (1999). They find a clear decrease in the CO abundance near 12 mag. Our results are not as dramatic as found in the higher resolution study, which allowed for more data points to be placed at higher extinctions. For instance, the Kramer et al. (1999) core shows a peak extinction in a 30" beam of ~28 mag; at a resolution of 50", this reduces to peak extinction of 16 mag. Thus, our sampling is lower in the exact regions where gas-phase depletions are most likely.

4.2. C$^{34}$S (and CS) Abundance

To derive the total density of C$^{34}$S, we use the similar method described for C$^{17}$O in the previous section. That is, with a density and temperature assumed (and constant) for each grid position, we perform a $\chi^2$ search for the best-fit total column density. For collision rates, we use the rates given by Green & Chapman (1978), and the line width is determined via Gaussian fits to the spectrum. C$^{34}$S does not have hyperfine structure, but we have additional information in that the C$^{34}$S opacity has been determined for all positions with greater than 3σ integrated intensities (§ 3.2). Thus, for each data point, we again have two constraints for the radiative transfer model: (1) the integrated intensity and (2) the opacity of the $J=2 \rightarrow 1$ transition. The majority of column density solutions have a reduced $\chi^2 < 1$.

The C$^{34}$S integrated intensity as a function of visual extinction is presented in Figure 12. This figure is notable in that the C$^{34}$S integrated intensity appears to be reasonably well correlated with A$_V$. This result is somewhat surprising given the near-constant opacity as a function of extinction shown in Figure 8. The near-uniform opacity would suggest that the C$^{34}$S (and therefore CS) abundance is sharply decreasing with extinction. However, the dependence in Figure 12 is at odds with that conclusion since it requires a constant abundance. This difference, an integrated intensity correlated with A$_V$, combined with a constant optical depth can be reproduced provided that there was a change in excitation from low to high extinctions. Indeed, we can expect such an increase in the C$^{34}$S excitation temperature proceeding from lower to higher A$_V$ as a direct result of the known density gradient. Even a small change in the excitation temperature could replicate the observed dependence.

The results of the C$^{34}$S excitation analysis are presented in Table 2 in the form of abundances and in Figure 11 as normalized abundance plotted against visual extinction. Examining the data points, we find a steady statistically significant abundance (> 3σ) decrease by an overall factor of 3 from low to high extinction. Thus, by accounting for the rise in density as required by the near-infrared observations and the observed constant opacity along with an integrated intensity that increases with extinction, we find that the CS abundance decreases with A$_V$. If we assume that the most likely temperature gradient is with warm gas at core edges ($T=13$ K) and cold gas ($T=5$ K) in the center, then the abundance still systematically declines by a factor of 2. In all, these results suggest that CS, like CO, shows an abundance decrease in the dense gas likely due to depletion onto grains.

4.3. N$_2$H$^+$ Abundance

To derive the abundance of N$_2$H$^+$, we use the total intensity of the lines along with the hyperfine ratios as described earlier for C$^{17}$O. We use the collisional rates for HCO$^+$ excited by para-H$_2$ (Flower 1999), which has comparable collisional rates to N$_2$H$^+$ (Monteiro 1984). The results of

![Figure 12](image)
the excitation calculations are given in Table 2 and shown in Figure 11.

First, there are only three N$_2$H$^+$ detections between 0 and 5 mag of extinction, and of these, two have $A_V > 4.5$ mag (these data are not provided because of high errors). Although C$^{34}$S and C$^{17}$O also have little emission in this regime, the more abundant isotopes, C$^{18}$O and CS, both are detected at low extinction. Thus, unlike for other species, there appears to be little N$_2$H$^+$ below $A_V \lesssim 4$ mag. Beyond the lowest extinctions, for $T = 10$ K, the N$_2$H$^+$ normalized abundance in Figure 11 shows a high abundance for low $A_V$ ($\sim 7.5$ mag) then decreases by a factor of 3 for $A_V = 17.5$ mag, whereupon the abundance increases by a similar factor at high $A_V$. In our solutions with different temperatures ($T = 5$, 10, and 13 K), we find that the initial abundance decrease for $A_V < 17.5$ mag is lessened, provided that the cloud is warmer in these regions. If the gas is cooler in the core center, then we find an even greater increase in relative abundance for $A_V > 17.5$ mag.

In summary, we find at least two regimes for the N$_2$H$^+$ abundance: (1) there is a threshold of extinction, $A_V^{th} \lesssim 4$ mag, below which we find little or no N$_2$H$^+$ in the gas-phase, and (2) for higher extinctions, the abundance shows a complicated structure that initially declines in value until $A_V = 15$ mag, whereupon the relative abundance increases with extinction. Consideration of potential temperature changes reduces the initial decline but would increase the rise in relative abundance toward the core center. However, there is no evidence for a systematic decrease in the N$_2$H$^+$ abundance at large $A_V$. In the following section we examine the physical and chemical causes that give rise to this dependence.

5. DISCUSSION

5.1. Differential Molecular Depletions in IC 5146

In the preceding section we examined the excitation of the three molecules included in our survey. The result of this analysis is that we find good evidence for the presence of differential molecular depletions in IC 5146. That is, C$^{18}$O and CS (and C$^{34}$S) are depleting from the gas phase at high extinctions, and N$_2$H$^+$ is not (at least at a resolution of 50$^\circ$). Similar evidence of differential depletions are found in the literature (for a summary, see Bergin 2000). The depletion of CCS relative to both ammonia and N$_2$H$^+$ (with the latter two tracers typically coincident with the dust continuum emission peak) found in isolated low-mass cores is quite similar to the results found in our work (Kuiper, Langer, & Velusamy 1996; Ohashi et al. 1999). Recently, Caselli et al. (1999) found evidence of CO depletion in the starless L1544 cloud core in a region traced by both N$_2$H$^+$ and dust continuum. The detection of gas-phase molecular depletions should not be considered unexpected given that molecular ice features have been observed along numerous lines of sight in the interstellar medium (Whittet 1993; Tielens et al. 1991).

In general, previous searches for chemical differences related to molecular depletion relied on finding morphological dissimilarities between the emission of two or more species with each other or with dust continuum (similar to that shown in Fig. 3) and then performing an excitation analysis to prove or disprove that such differences are the result of chemical abundance variations. Our study has found comparable results but has placed the evidence for molecular abundance changes, which are attributed to depletion, on firmer statistical ground and removed any ambiguity in terms of the total hydrogen column density, such as those associated with using dust continuum emission (Kramer et al. 1998).  

5.2. Comparison with Chemical Theory

This depletion pattern with sulfur-bearing molecules (e.g., CS, CCS) along with CO showing depletions onto grains and N$_2$H$^+$ remaining in the gas phase are in good agreement with the theoretical models presented by Bergin & Langer (1997). In these models, the gas-phase chemistry includes the effects of molecules both depleting onto and evaporating from grain surfaces. N$_2$H$^+$ remains in the gas phase longer at higher densities than other molecules because the high volatility of its precursor molecule N$_2$ allows for various desorption mechanisms (such as thermal evaporation or cosmic-ray spot heating of grain surfaces) to keep a significant N$_2$ abundance, and therefore N$_2$H$^+$, in the gas phase at high densities.

To compare our results with the gas-grain chemical model of Bergin & Langer (1997), we use the density profile given in Figure 10. This profile matches the one derived for IC 5146 from the near-infrared extinction measurements (LAL99). We adopt the notation $\tau_V$ with regards to cloud depth because the model is computed using cloud radius, thus, $A_V = 2\tau_V$. With extinction and density (we also assume a constant dust and gas temperature of 10 K and a UV enhancement factor of $G_0 = 2.2$; Kramer et al 1999) predetermined as a function of radius, we use the chemical model of Bergin & Langer (1997) to predict abundances as a function of both time and visual extinction and then directly compare these to the observational results. This model is slightly different from Bergin & Langer (1997) in that we do not allow for the density to evolve with time but rather hold the density constant for each radius (and therefore extinction). However, the density does increase with increasing extinction, properly matching the observed structure.

Figure 13 presents two different chemical models. The top two panels show a pure gas-phase chemical model sampled at two different times (10$^4$ and 10$^7$ yr). This model includes the effects of grain-absorbing UV radiation (thereby allowing for molecular formation) but does not include any gas-grain interactions. We note that to match the models to observations, $\tau_V$ must be multiplied by a factor of 2 to account for both sides of the cloud (i.e., the model was done using radius and not diameter). In Figure 13 we see that the abundances of most species rise as the UV radiation field is attenuated with increasing extinction and then remain constant. This behavior exists despite the nearly 2 order of magnitude rise in density from edge to center. However, for N$_2$H$^+$, there is a slow steady decrease in abundance toward greater extinction. This behavior is readily understood by examining the primary formation and destruction processes for N$_2$H$^+$. Using the pathways outlined in Appendix A, we see that the formation rate of N$_2$H$^+$ (via cosmic-ray ionization) should be essentially con-

\* Of course, another method to search for molecular depletions is to directly observe molecules in the solid state. This method works quite well for the dominant molecules on grain surfaces (such as H$_2$O or CO). However, it fails for lesser abundant species such as CS because, even if they depleted entirely from the gas phase, their abundances are too low to produce observable absorption features.
Figure 13.—Profile of gas-phase abundances (abundances are relative to $H_2$) against optical depth for surveyed species and $N_2$. The top panels are a pure gas-phase chemical model, while the lower panels are a gas-grain chemical model. Similarly, the left-hand panels are for time $t = 10^5$ yr, and the right-hand panels for $t = 10^7$ yr. The physical conditions of the model are given in § 5.2.

The second model shown in the bottom two panels of Figure 13 is a gas-grain chemical model, in which molecules are allowed to collide and stick to the surfaces of dust grains. The primary desorption mechanism is cosmic-ray spot heating. For the binding energy of molecules to the grain surfaces, we assume that the grains are coated by a layer of CO molecules. For more details of the model, see Bergin & Langer (1997). Comparing the pure gas-phase model with the gas-grain model at $t = 10^5$ yr, the abundance profiles are similar. At this early time, depletion has yet to play a role. For later times, we see demonstrative effects due to grain depletion: (1) For $\tau_V > 6$ mag ($A_V > 12$ mag), the abundance of CS is dramatically reduced. (2) The abundance of CO shows a small, factor of $\sim 3$, decrease between $\tau_V = 0$ and 16 mag. (3) The abundance of $N_2H^+$ is constant with $A_V$. For $N_2H^+$, this behavior is in direct contrast to that seen in the pure gas-phase case. This indicates that the $N_2H^+$ destruction rate must be progressively lower with higher extinction and density in the gas-grain model than for pure gas-phase chemistry. From Appendix $A$, the major destroyers of $N_2H^+$ are CO and electrons. In Figure 13 there is increasing CO depletion with higher density and extinction, which results in a progressively lower $N_2H^+$ destruction rate. Thus, the observed uniform abundance of $N_2H^+$ at high extinctions is also a direct consequence of CO depletion and is not solely the result of the high volatility of the $N_2$ molecule. It is worth noting that if more CO molecules freeze onto grains, as would occur when time progresses, then $N_2H^+$ abundance rises accordingly.

Finally, we note that at low $A_V$ for CS and CO [$x(C^{18}O) \times 500$], the models can be directly compared to the observed abundances, and predicted values are in reasonable agreement with observations (compare Figs. 11 and 13). For high $A_V$, the models, as presented here as abundance profiles with extinction, cannot be directly compared to the observations. This is because the observations are
averages over the entire line of sight, including both depletion zones and undepleted gas. For a direct comparison, the chemical model would have to be averaged over the line of sight, stepping through $A_V$, in similar fashion to the observations. However, this is not the case for undepleted species (e.g., $\text{N}_2\text{H}^+$), which can be directly compared to observations. If the relative abundance profile in Figure 11 is correct, then the observations would suggest a combination of undepleted models (to account for the low $A_V$, decline in abundance), and the depleted models (accounting for the rise in abundance at high extinction) would be required. In each case, the models are in reasonable agreement with the overall value of abundance.

5.3. Testing Interstellar Photodissociation Rates

In § 4.3 we found two regimes for the $\text{N}_2\text{H}^+$ abundance: (1) there is a threshold extinction, $A_V^{\theta} \lesssim 4$ mag, below which there is little or no $\text{N}_2\text{H}^+$, and (2) for higher extinctions, the abundance is roughly constant. In the previous section we discussed how the structure in the latter regime can be reproduced. However, in Figure 13 the dependence found in the former regime is also addressed. In the chemical model the lack of $\text{N}_2\text{H}^+$ for $A_V \lesssim 4$ mag is the result of the photodissociation of its parent molecule ($\text{N}_2$) combined with a higher electron abundance at cloud edges because of photionization. In Figure 13, $\text{N}_2\text{H}^+$ shows a sharp rise in abundance for $\tau_V \sim 3$ mag corresponding to $A_V \sim 6$ mag. This is quite close to the observed threshold. The $\text{N}_2$ photorate is taken from van Dishoeck (1988), in which the depth dependence of the photodissociation rate depends on its absorption cross section, the assumed radiation field, the continuum attenuation, and the albedo and scattering phase function of the grains (van Dishoeck 1988). Despite the complications involved in this computation, given the match between the observed and predicted threshold, the depth dependence of the rate and the ionization structure appears to be reasonably taken into account.

We note that the chemical model in Figure 13 does not properly account for the self-shielding of CO molecules since $\text{C}^{18}\text{O}$ is emission is observed for $A_V < 4$ mag (Fig. 6). However, the effect of increased CO shielding in the model would be to lower the electron abundance at the cloud edge and increase the importance of $\text{N}_2$ photodestruction as the method for lowering the $\text{N}_2\text{H}^+$ abundance. Our assertion that $\text{N}_2$ photodissociation is contributing to the observed $\text{N}_2\text{H}^+$ abundance threshold would then be strengthened.

Van Dishoeck (1988) presents a different photorate computed using a different grain model than used in our model, one with the grains more forward-scattering (their grain model 3). If we use the depth-dependent photorates from that model (for all steps in $\text{N}_2$ and $\text{N}_2\text{H}^+$ production), we find that the $\text{N}_2$ photodissociation rate is larger deeper into the cloud, and the $\text{N}_2\text{H}^+$ threshold shifts to beyond $A_V = 10$ mag. This is in disagreement with the observations and points to an important use of the technique outlined in this paper. In the future, by observing and modeling clouds with simple and well-characterized structure, the depth-dependent photorates (along with the gas-grain interaction) can be tested. Indeed, most of the depth-dependent photorates for many molecules are highly uncertain (van Dishoeck 1988). In some cases, this is due to a lack of viable cross sections but also because the detailed rate calculations could not be observationally verified. Although there certainly are complications in application, this technique offers a viable opportunity to provide observational tests of these rates, which can help in constraining not only the depth dependence of the photorates but also the grain physics.

6. SUMMARY

We have examined the correlation of the emission of three molecules, $\text{C}^{18}\text{O}$, CS, and $\text{N}_2\text{H}^+$, with visual extinction in the northern streamer of the IC 5146 cloud. We use the molecular data along with a model of the excitation to determine molecule abundances and examine the abundance profile with $A_V$. The principle results are as follows:

1. We find good evidence for a reduction in the abundance of CO and CS (using $\text{C}^{18}\text{O}$) for $A_V \gtrsim 10$–15 mag. This reduction is attributed to the depletion of these molecules onto the surfaces of cold dust grains in the densest portions of the IC 5146 cloud.

2. For $\text{N}_2\text{H}^+$, we find two separate regimes for its abundances: (a) for low extinction, there is a threshold extinction $A_V^{\theta} \lesssim 4$ mag, below which little $\text{N}_2\text{H}^+$ is found, and (b) for $A_V \gtrsim 4$ mag, the $\text{N}_2\text{H}^+$ abundance is either constant or declining until $A_V = 15$ mag, whereupon the abundance rises as a function of extinction in the visual.

3. We find that density gradients in cloud cores can have a profound effect on the derivations of the spatial distributions of total column densities and molecular abundances for species with high dipole moments. Chemical interactions, such as reaction rates and depletion timescales, are also strongly density-dependent. Thus, the interpretation and determination of accurate abundances in dense cloud cores require both knowledge of the density and temperature structure in the cloudy material and a proper accounting for such structure in abundance determinations and chemical models.

4. The observed patterns of differential depletion show CS and CO exhibiting molecular depletions, while $\text{N}_2\text{H}^+$ remains in the gas phase. This is in good agreement with the predictions of chemical theory by Bergin & Langer (1997).

5. By combining the observationally derived density profile for IC 5146 from LAL99 with the gas-grain chemical model of Bergin & Langer (1997), we show that the observed constant $\text{N}_2\text{H}^+$ abundance with extinction can be reproduced provided that CO, which is a major destroyer of $\text{N}_2\text{H}^+$, is depleting in the dense cores. Since CO depletion is observed, this result is an important clue to the physical and chemical reason that allows $\text{N}_2\text{H}^+$ molecules to trace the densest regions of molecular cores.

6. We also demonstrate that the observed $\text{N}_2\text{H}^+$ abundance threshold ($A_V^{\theta} \lesssim 4$ mag) is partially due to the photodissociation of $\text{N}_2$. This highlights an important application of this technique, which is the ability to test not only the chemical models of dense regions, and thereby directly probe the gas-grain interaction, but also to provide a viable and completely new method for observationally testing models of depth-dependent photodissociation rates.

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APPENDIX A

FORMATION OF $\text{N}_2\text{H}^+$ ABUNDANCE

The primary route to form $\text{N}_2\text{H}^+$ is through the following reaction:

$$\text{H}_3^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}_2 \ . \quad (A1)$$

$\text{H}_3^+$ is produced via cosmic-ray ionization of $\text{H}_2$. The main destruction pathways are dissociative electron recombination and a reaction with CO (reactions with O and C are of lesser import). In equilibrium, the following expression can be derived for the concentration of $\text{N}_2\text{H}^+$:

$$n(\text{N}_2\text{H}^+) = \frac{n(\text{H}_3^+)n(\text{N}_2)k_{\text{H}_3^+, \text{N}_2}}{n(e^-)\alpha(\text{N}_2\text{H}^+) + n(\text{CO})k_{\text{CO, N}_2\text{H}^+}}, \quad (A2)$$

where $\alpha(\text{N}_2\text{H}^+)$ is the dissociative recombination coefficient and $k_{X, \text{N}_2\text{H}^+}$ are the various reaction rates given by Millar, Farquhar, & Willacy (1997). See also Womack, Ziurys, & Wycko† (1992).

REFERENCES

Alves, J., Lada, C. J., & Lada, E. A. 1999, ApJ, 515, 265
Alves, J., Lada, C. J., Lada, E. A., Kenyon, S. J., & Phelps, R. 1998, ApJ, 506, 292
Bergin, E. A. 2000, in IAU Symp. 197, Astrochemistry: From Molecular Clouds to Planetary Systems, ed. Y. C. Minh & E. F. van Dishoeck (San Francisco: ASP), 51
Bergin, E. A., Goldsmith, P. F., Snell, R. L., & Ungerechts, H. 1994, ApJ, 431, 674
Bergin, E. A., & Langer, W. D. 1997, ApJ, 486, 316
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 224, 132
Carter, V. 1972, J. Chem. Phys., 56, 4195
Caselli, P., Myers, P. C., & Thaddeus, P. 1995, ApJ, 455, L77
Caselli, P., Walmsley, C. M., Tafalla, M., Dore, L., & Myers, P. C. 1999, ApJ, 523, L165
Ciardi, D. R., Woodward, C. E., Clemens, D. P., Harker, D. E., & Rudy, R. J. 1998, AJ, 116, 349
Dobashi, K., Yonekura, Y., Mizuno, A., & Fukui, Y. 1992, AJ, 104, 1525
Flower, D. R. 1988, Molecular Collisions in the Interstellar Medium (Cambridge: Cambridge Univ. Press)
---. 1999, MNRAS, 305, 651
Green, S., & Chapman, S. 1978, ApJS, 37, 169
Jenkins, E. B., & Savage, B. D. 1974, ApJ, 187, 243
Jijina, J., Myers, P. C., & Adams, F. C. 1999, ApJS, 125, 161
Kramer, C., Alves, J., Lada, C., Lada, E., Sievers, A., Ungerechts, H., & Walmsley, M. 1998, A&A, 329, L33
Kramer, C., Alves, J., Lada, C., Lada, E., Sievers, A., Ungerechts, H., & Walmsley, M. 1999, A&A, 342, 257
Kuiper, T. H., Langer, W. D., & Velusamy, T. 1996, ApJ, 468, 761
Lada, C. J., Alves, J., & Lada, E. A. 1999, ApJ, 512, 250 (LAL99)
Lada, C. J., Lada, E. A., Clemens, D. P., & Bally, J. 1994, ApJ, 429, 694
Ladd, E. F., Fuller, G. A., & Deane, J. R. 1998, ApJ, 495, 871
Mathis, J. S. 1990, ARA&A, 28, 37
Millar, T. J., Farquhar, P. R., & Willacy, K. 1997, A&AS, 121, 139
Monteiro, T. 1984, MNRAS, 210, 1
Ohashi, N., Lee, S. W., Wilner, D. J., & Hayashi, M. 1999, ApJ, 518, L41
Penzias, A. A. 1981, ApJ, 249, 518
Pratap, P., Dickens, J. E., Snell, R. L., Miralles, M. P., Bergin, E. A., Irvine, W. M., & Schloerb, F. P. 1997, ApJ, 486, 862
Reike, G. H., & Lebolsky, M. J. 1985, ApJ, 288, 618
Richards, P. G., Torr, D. G., & Torr, M. R. 1981, J. Geophys. Res., 86, 1495
Shirley, Y. L., Evans, N. J., II, Rawlings, J. M. C., & Gregersen, E. M. 2000, ApJS, 131, 249
Tielens, A. G. G. M., Tokunaga, A. T., Geballe, T. R., & Baas, F. 1991, ApJ, 381, 181
van Dishoeck, E. F. 1988, in Rate Coefficients in Astrochemistry, ed. T. J. Millar & D. A. Williams (Dordrecht: Kluwer), 49
van Dishoeck, E. F., & Black, J. H. 1988, ApJ, 334, 771
Whittet, D. C. B. 1993, in Dust and Chemistry in Astronomy, ed. T. J. Millar & D. A. Williams (Bristol: IOP), 9
Womack, M., Ziurys, L. M., & Wycko†, S. 1992, ApJ, 387, 417