INTERSTELLAR FORMALDEHYDE

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1. Introduction

Formaldehyde (H_2CO) was found to be present in the interstellar medium less than 1½ yr ago [1]. This discovery raised a number of new astrophysical problems specific to H_2CO such as how is the molecule formed, how is it destroyed, and how do the anomalous energy level populations leading to absorption of the isotropic microwave background arise. In addition, H_2CO has provided a new means of studying several problems of long standing interest in astronomy. These include large scale galactic structure, distribution and motions of local gas and dust, and isotopic abundance ratios. A surprisingly large amount of work has been done on these problems in the rather short time since the initial discovery. I will confine myself to a brief summary of the observational aspects, omitting many of the topics that will be discussed in more detail by others later today, and then describe in detail some of our more recent work.

2. The H_2CO Molecule

First we briefly consider the molecule and its spectrum. Figure 1 shows the lowest rotational energy levels of $H_2C^{12}O^{16}$. It is an asymmetric top molecule: the three principle moments of inertia are unequal. Therefore for each total angular momentum, J, there are $2J+1$ levels [2]. There are three important things to notice about the energy level scheme. First, because the asymmetry is small, closely spaced pairs of levels occur. It is these pairs that are responsible for the radio frequency lines observed. Second, the energy levels are divided into two classes according to their symmetry: the ortho and the para [2]. Transitions between the two classes are very strongly forbidden [1]. All of the transitions so far observed are in the ortho-series for which the 1_{11} can be considered as a ground state. Third, the spacing between the pairs of levels corresponds to temperatures of 10's of degrees so that if collisions are frequent enough to dominate other processes, doublets other than the lowest can have significant populations even at fairly low temperatures. Finally, the energy level scheme for $H_2C^{13}O^{16}$ looks very similar, but slightly compressed. The presence of the additional spin of the C^{13} nucleus does not affect the symmetries.

Four transitions of H_2CO have been observed to date: the lowest three doublets in $H_2C^{12}O^{16}$ (the 1_{11}–1_{10} at 4829.660 MHz [1], the 2_{12}–2_{11} at 14488.65 MHz [3], and the 3_{13}–3_{12} at 28974.85 MHz [4]) and the lowest in $H_2C^{13}O^{16}$ (the 1_{11}–1_{10} at 4593.08 MHz [5]).

The initial identification as H_2CO was based on the coincidence in rest frequency of the astronomically observed line and that of the 1_{11}–1_{10} line in $H_2C^{12}O^{16}$. The

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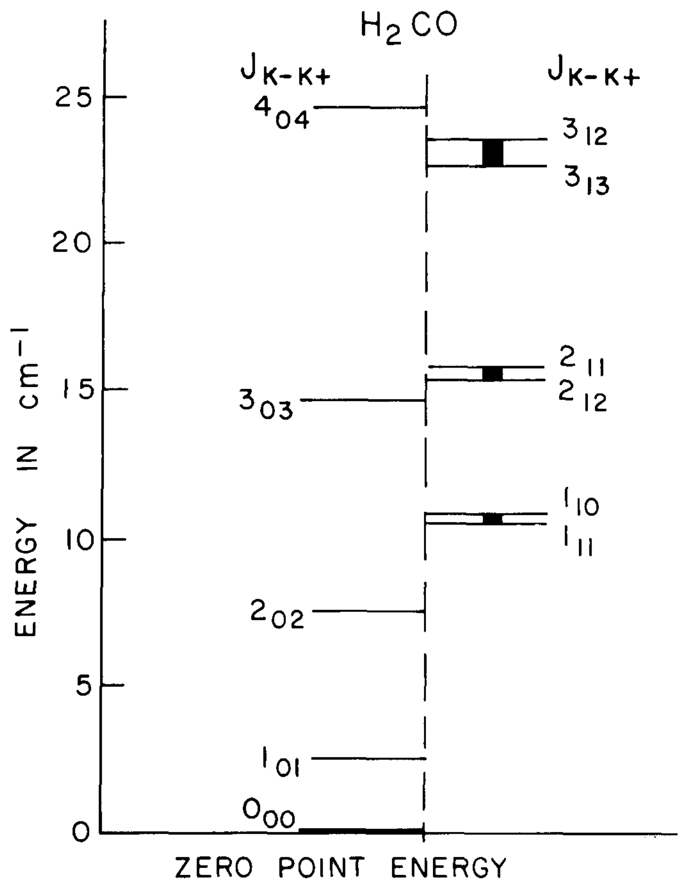

Fig. 1. Energy levels of $H_2C^{12}O^{16}$. The transitions observed to date are indicated by bars connecting the levels.

coincidence with the one line could have been questioned as accidental, but the subsequent detection of the C^{13} – substituted species and of the other two transitions remove any doubt that we have indeed observed H_2CO.

3. General Distribution and Abundance

Next we will consider the general distribution and abundance of H_2CO. First, where is H_2CO observed? The answer is nearly everywhere. Absorption is seen against all the usual types of continuum sources – HII regions, supernove remnants, and extragalactic sources – as well as in dark dust clouds where absorption is seen against the isotropic microwave background. H_2CO has not been seen in the direction of infrared stars that are prominent OH and H_2O microwave emission sources nor in those containing the peculiar infrared emission feature attributed to silicates [6]. In these cases the other molecules seen are presumably circumstellar so the beam dilution factor could well account for the failure to detect H_2CO even if it is present. Also, we do not see H_2CO in the direction of stars with strong interstellar absorption lines [6]. The rule seems to be that if one sees bright stars, he will not see H_2CO. This suggests that the H_2CO must be protected from the general interstellar radiation field in order to be abundant enough to be seen. No H_2CO emission has been seen yet, which suggests the excitation temperature for the 1_{11}–1_{10} transition is always equal to or less than the microwave background temperature of 2.7K.

Returning to the absorption against discrete continuum sources, in our initial survey [7] we found absorption against 23 of the 43 sources or source components observed. (These included both galctic and extragalactic continuum sources.) Whiteoak and Gardner [8] found absorption in 31 of 34 galactic sources. The radial velocities of H_2CO features often correspond to those of spiral arm features identified in 21 cm hydrogen studies. In some cases the H_2CO containing cloud is probably related to the continuum source.

The general distribution then is similar to that of neutral hydrogen, although H_2CO is by no means uniformly mixed with the H I. Detailed comparisons of H_2CO results with those for H I and OH absorption are hampered at present by the differences in antenna beamwidths in the various studies, but it is possible to make a few general statements. In the sources studied by Zuckerman *et al.* [7] about 50% of the 21 cm hydrogen absorption features correspond to H_2CO features. The average ratio of H I concentration to H_2CO concentration is $\approx 10^8$, assuming for example 60 K for the excitation temperature for the hydrogen and 3 K for H_2CO (the concentration ratio probably varies by a factor of 100 from source to source.) In many of these cases, the H_2CO lines are narrower than the H I lines. Of these cases, often turbulent broadening dominates, so the narrowness of the H_2CO lines implies H_2CO is more localized than H I in these directions. A simple picture yielding this result is that the H_2CO is concentrated towards the centers of clouds where it is more protected from dissociating radiation. This picture then suggests further caution in the interpretation of the hydrogen atom/H_2CO molecule concentration ratio.

In the comparison of H_2CO with OH absorption the correspondence between the two species is much closer. In the sources we observed 80% of the OH absorption features corresponded to H_2CO features, and no source showing H_2CO absorption failed to show OH absorption. The concentration ratio for OH to H_2CO is ≈ 30, assuming, for example, the excitation temperature of ≈ 10K for OH and 3K for H_2CO.

4. C^{13} – Substituted H_2CO

There is great potential value of microwave observations for isotopic abundance determinations. This is to a large measure because of the fact that in optical spectra, where electronic transitions are involved, the separation of lines from different isotopes is usually small and often less than a linewidth. At microwave frequencies we are usually looking at rotational lines – where the mass is precisely the thing that matters – so separations are usually large. For example, the difference between the rest frequency of the 1_{11}–1_{10} transition for $H_2C^{13}O^{16}$ and that for $H_2C^{12}O^{16}$ corresponds to a doppler shift of 5% of the velocity of light!

Last year we detected the C^{13}-substituted H_2CO [5]. Recently we have re-observed $H_2C^{13}O^{16}$ with a better receiver and have made detections in several additional sources [9]. We can determine the C^{12}/C^{13} abundance ratio directly from the observations if we make three assumptions: the formation process for the molecule does not preferentially select one isotope, the energy levels are populated in the same manner for both C^{12}- and C^{13}-substituted H_2CO, and the absorbing cloud uniformly covers the continuum source. We have no reason to question the first assumption at present, the second is valid in the absence of pumping effects such as those that must be taking place in the dark clouds (see Section 6) and even if these processes are important the assumption will not necessarily be invalid. The third assumption is more questionable, at least in some cases which will be discussed in the next section.

TABLE I

C^{12}/C^{13} Abundance ratios from H_2CO lines

Source	C^{12}/C^{13}
Sgr A [a]	11^{+8}_{-2}
Sgr B2 [a]	11 ± 2
W33N [b]	105 ± 30
W51 [b]	63 ± 20
NGC 2024 [b]	$\gtrsim 84$
Cas A [a]	> 40
Terrestrial value: 89	

[a] Reference [5]
[b] Reference [9]

Table I shows the abundances determined with the three assumptions stated. In the galactic center sources we find apparent C^{12}/C^{13} abundance ratios about ten times the terrestrial value, while the values for the other sources are clustered around the terrestrial value. The galactic center region is discussed separately in the next section. The present conclusion is that except for the galactic center we have no convincing evidence that the C^{12}/C^{13} ratio departs from the 'normal' terrestrial one. At this point it is well to recall that we cannot at present explain the terrestrial C^{12}/C^{13} ratio, so we should be careful what we call normal.

5. The Galactic Center

Several interesting problems have shown up in H_2CO studies of the galactic center region (more precisely in the Sgr B2 direction and that of the position at which NH_3 was first detected [10]). First, as discussed above, the ratio of apparent optical depths of the 1_{11}–1_{10} lines for C^{12}- and C^{13}-substituted H_2CO is about 10; second, the apparent optical depth of the 2_{11}–2_{12} line is approximately equal to that of the 1_{11}–1_{10} line [3]; and third, the apparent optical depth of the 3_{13}–3_{12} line is also approximately equal to that of the 1_{11}–1_{10} line [4]. The factors involved in determining the relative optical depths are the isotopic abundance ratio, the excitation temperature within the doublets, the excitation temperature between the doublets, and the distribution of H_2CO across the source (which must be known to convert apparent optical depths to true optical depths).

At present it seems that no single one of these factors can simultaneously explain the three observations. For example, if the excitation temperatures are close to the microwave background temperature of 2.7K, and the 3_{12}–3_{13} result is explained by the H_2CO being highly clumped so that the assumption of the source being uniformly covered is not valid, then either the C^{13} abundance must be very significantly *less* than the terrestrial value or the excitation must be different for the C^{13}-substituted molecules. On the other hand interpretations involving high excitation temperatures are difficult to fit because all the lines are seen in absorption. Before these factors can be sorted out, more detailed observations of all of the lines will be required.

It is also interesting to note several other results: the discovery of a very large cloud containing NH_3 in the Sgr B2 direction, the subsequent interpretation that it must have particle densities greater than 10^3 cm^{-3} [10], and the detection of the most complex molecule so far, cyano-acetylene [11], in this same direction. At present it is not possible to draw any but the most tentative conclusions about this interesting region, but it seems to me very likely that a combination of high densities leading to high excitation temperatures as well as isotopic abundance anomalies may be required to explain the data.

6. The Dark Clouds

Last year we were rather surprised to find that in the direction of optically prominent dark nebulae H_2CO was seen in absorption even though there was no continuum source present except the isotropic microwave background [12]. This means that in these nebulae the excitation temperature for the 1_{11}–1_{10} doublet is less than the temperature of the environment, and that some non-thermal process is transferring molecules from the upper to the lower level of the doublet: just the inverse process of maser amplication. Explanations for this phenomenon have been offered by Townes and Cheung [13], by Litvak [14], and by Thaddeus and Solomon [15]. I will not discuss them, as the excitation problem is discussed by others at this symposium. Instead I will discuss our observations.

Figure 2 shows a high signal-to-noise spectrum of Heiles' cloud 2: a dust cloud in Taurus. The solid line is the spectrum constructed from H_2CO hyperfine components measured in the laboratory [16], assuming gaussian line shapes with full widths at half power of 0.28 km sec^{-1}, and smoothing to the instrumental resolution. The agreement is very good except near 5.9 km/sec. Thus we conclude that we see the hyperfine components in the interstellar medium, that to within the noise they are populated according to thermal equilibrium, and that there must be another velocity

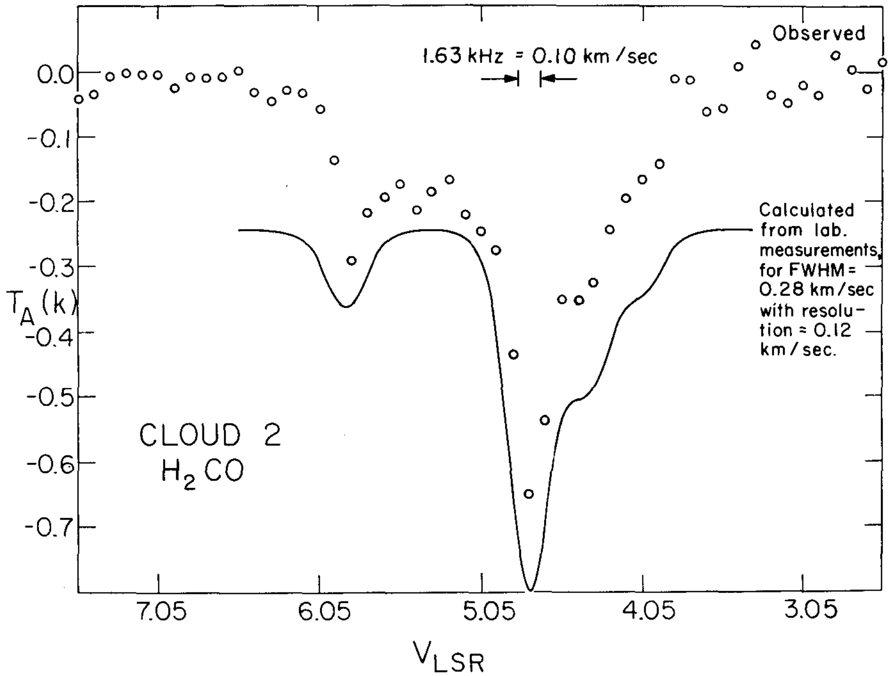

Fig. 2. Open circles: observed spectrum in the direction of Heiles' Cloud 2 (1950 coordinates: $\alpha = 4^h38^m30^s$, $\delta = 25°18'$). Solid curve: fitted spectrum constructed as described in text. The observed points are spaced by 1.63 kHz and the effective resolution is 2 kHz. A constant of 0.62 km/sec must be added to the velocities indicated on the ordinate to correspond to the rest frequency obtained by Tucker *et al.* [18] and used in the text. This rest frequency is to be preferred to the older value used in all previous references.

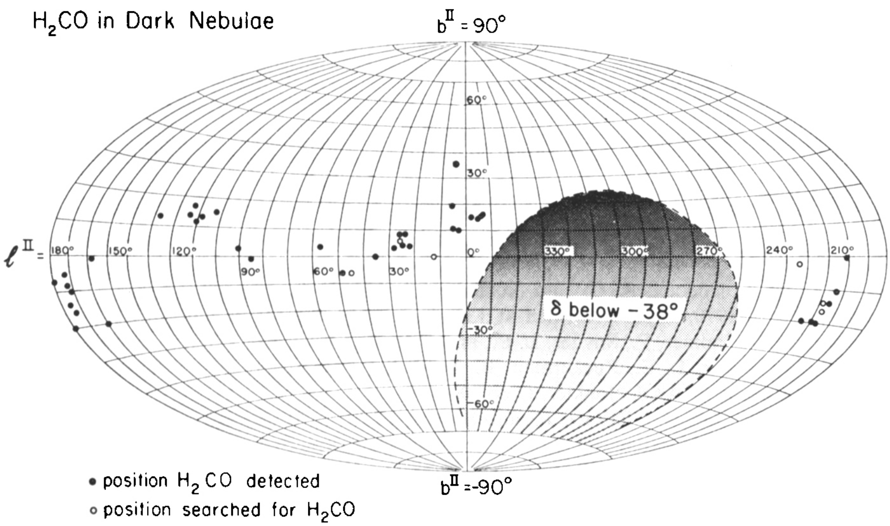

Fig. 3. Dark nebulae observed for H_2CO absorption. Filled circles: H_2CO detected; open circles: H_2CO not detected. Shaded area is the area of the sky that does not rise at least 10° above the horizon in Green Bank, West Virginia.

component in this cloud with $\sim\frac{1}{2}$ km/sec higher velocity. I wish to emphasize the extreme sharpness of this line and others in dark clouds; 0.28 km/sec corresponds to a kinetic temperature of ~ 50K. Figure 3 shows the distribution of dark nebulae observed. I wish to emphasize that these dark clouds were chosen for being prominent in the Palomar survey and not for any radio criteria. Thus they are indeed local material. All of the well-known regions are represented: Orion, Scorpius, Ophiuchus, and Taurus. We see H_2CO in at least 32 of 43 regions, i.e. in nearly every dark cloud. When we compare with the survey of Heiles and Cudabeck [17], we find that H_2CO is seen in significantly more cases than OH is. This may be because more special conditions are required for OH emission than for H_2CO absorption or because of antenna beam dilution effects (though the latter seems unlikely because the H_2CO seems to be so widespread in these directions). Another interesting but at present unprovable possibility is that in some cases all of the OH radicals have been used up in forming more chemically stable molecules. More detailed observations of both OH and H_2CO are necessary to settle this question, but in any case it is striking that H_2CO absorption is seen in nearly every optically prominent dark nebula.

7. Conclusion

So far H_2CO studies seem to have been of greatest value when applied to such problems as abundance determinations, study of local gas and dust, and galactic dynamics [18, 19] (which I unfortunately haven't had time to discuss). Some of the very interesting problems outlined in the introduction dealing with the H_2CO observations themselves have as yet not yielded to the investigations (as was probably more obvious from my omissions than from what I discussed). I believe we can expect important progress on both classes of problems in the next few years.

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DISCUSSION

Weliachew: I would like to mention preliminary results from work currently being done at Cal Tech by E. Fomalont and myself. We have looked at formaldehyde absorption in the Galaxy with the twin element interferometer in order to determine sizes and positions of absorbing clouds. In the case of Sag A, our results will not admit a ratio of C_{12}/C_{13} higher than 25 which may compared with the 11 quoted by Dr Palmer under the assumption of uniform coverage.