[7]An example of a C function is

$$C(\alpha_c(t), \alpha(u)) = \int_{-L+\alpha_c(t)}^{\alpha_c(t)} dl\, (\alpha_c - l)(\alpha_c - L - l) \times \frac{\Gamma(1-l)\Gamma(1-\alpha(u))}{\Gamma(1-\alpha(u)-l)}$$

from unpublished work by A. Schwimmer and S. Pinsky.

[8]We only mention a few examples: S. Frautschi and B. Margolis CERN Preprint No. Th CERN 909 (to be published); G. Veneziano, Massachusetts Institute of Technology Preprint No. CTP 51 (to be published).

MICROWAVE DETECTION OF INTERSTELLAR FORMALDEHYDE

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Interstellar formaldehyde (H_2CO) has been detected in absorption against numerous galactic and extragalactic radio sources by means of the 1_{11}-1_{10} ground-state rotational transition at 4830 MHz. The absorbing regions often correspond in velocity with 18-cm OH features. H_2CO is the first organic polyatomic molecule ever detected in the interstellar medium and its widespread distribution indicates that processes of interstellar chemical evolution may be much more complex than previously assumed.

The 140-ft telescope of the National Radio Astronomy Observatory was used to detect the 1_{11}-1_{10} transition of interstellar formaldehyde at 4830 MHz in absorption against numerous continuum radio sources. The 6_{25}-6_{24}, $13_{3\,11}$-$13_{3\,10}$, and $21_{4\,18}$-$21_{4\,17}$ transitions[1] were also searched for but not detected. Due to the present widespread interest in interstellar molecules and because a detailed analysis of all of our data will take some time, in this Letter we briefly report a portion of our results.

The 140-ft telescope was equipped with a cooled parametric amplifier and a 400-channel autocorrelation receiver. Spectral resolutions of 1, 2, 4, 8, and 16 kHz were used. The system temperature and aperture efficiencies were about 100°K and 50%, respectively. The half-power width of the antenna beam was ~6.6′. The radiometer was operated with frequency switching in the first local oscillator. The oscillator was locked to a rubidium standard which had a long-term stability of 2 parts in 10^{11}.

The 4830-MHz line was detected in absorption against the following continuum sources: M17, W3, W3 (OH position), W49, NGC 2024, DR 21, W43, W44, W51, Sgr A, Sgr B2, W33, NGC 6334, Cas A, and 3C 123. The line was not detected in NML Cyg, DR 23, 3C 273, Orion A, W28, VY CMa, Virgo A, Taurus A, Cygnus A, Venus, and Jupiter. Figure 1 shows an H_2CO spectrum of the galactic center (Sgr A) in which numerous absorption features are present. This spectrum closely resembles the OH absorption spectrum in the same direction.[2] For features with half-power widths <30 kHz the hyperfine splitting[3] must be considered. The hyperfine components of the line are not indicated in Fig. 1 since they are not resolved. Typical spectra contain between one and eight Doppler features. These features have full widths at half-maximum power ($\Delta\nu$) ranging from 15 to 500 kHz and peak antenna temperatures between 0.2 and 5°K. For sources in which no lines were detected the lower limits for detection are <0.5°K depending on linewidth. H_2CO emission was also sought adjacent to some of the continuum sources, but none is evident at the present stage of data reduction.

At least some of the observed features appear to originate in "typical" interstellar clouds (densities ~ 10 hydrogen atoms/cm^3, kinetic temperatures 50-100°K), some of which are associated

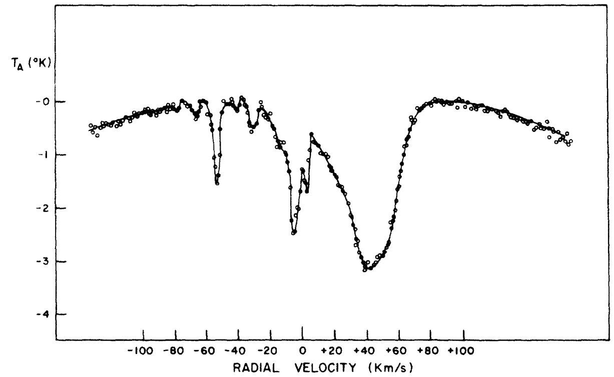

FIG. 1. Formaldehyde absorption against the galactic center (Sgr A). The ordinate is antenna temperature and the abscissa is radial velocity with respect to the local standard of rest. This spectrum closely resembles the OH absorption spectrum in the same direction. The effective resolution is ~1 km/sec.

with spiral arms. Other features appear to be physically related to the continuum sources they absorb. Hence it appears that the molecule H_2CO is widely distributed throughout the galaxy.

The laboratory rest frequency of the most intense hyperfine component[3] of H_2CO ($F = 2 \rightarrow F' = 2$) is 4829.649 ± 0.0005 MHz. By use of our Cas A and NGC 2024 spectra we have determined the rest frequency of the interstellar lines to be 4829.659 ± 0.010 MHz by assuming that they have the same Doppler shifts as the 18-cm OH and 21-cm H absorption lines in these directions. We regard the close coincidence of the astronomical and laboratory rest frequencies as a strong argument in favor of the identification with H_2CO since we find no other molecule[4] composed of astrophysically abundant elements that has a microwave line with a rest frequency that lies within our error bars. If some other molecule is found that has the astronomically measured rest frequency, a conclusive identification will require detection of other microwave transitions of either molecule.

It is not surprising that we were unable to detect the 6_{24}-6_{25}, $13_{3\,10}$-$13_{3\,11}$, and $21_{4\,17}$-$21_{4\,18}$ lines at 4955, 5137, and 5139 MHz, respectively, since under typical interstellar conditions these energy levels should have negligible populations. In the case of those sources containing strong microwave emission signals from water vapor,[5] our null result for these lines might provide an interesting test for any future water-vapor pumping model since the formaldehyde energy levels involved are about 85, 300, and 700 cm^{-1} above the zero-point energy. Detection of the 1_{11}-1_{10} line may be understood from the H_2CO energy-level diagram in Fig. 2. Since the electric dipole moment of this molecule is along the axis of the smallest moment of inertia, electric dipole transitions from either the 1_{10} or 1_{11} level to any of the three lower levels are forbidden by the selection rules.[6] Thus the long radiative lifetime for molecules in the 1_{11} level together with a fairly large ground-state dipole-moment matrix element greatly enhanced our chances of detecting this transition.

Because we did not observe 4830-MHz emission or a second transition, we are unable to reliably estimate the excitation temperature (T_μ) which characterizes the relative population distribution between the 1_{11} and 1_{10} levels. However, because these states are connected by an electric dipole transition it is reasonable to expect that in a typical interstellar cloud this excitation temperature may be low,[7] and in the discussion that follows we therefore consider $T_\mu \approx 10°\text{K}$. For calculation of H_2CO projected densities we consider two temperatures T_μ and T_S, where T_S is the temperature characterizing the relative populations in the 1_{11} and 0_{00} levels. Based on the considerations presented above, we expect that $T_\mu \lesssim T_S$ and also $T_S \approx T_{\text{kin}}$. since the effective collision time between the 1_{11} and 0_{00} levels may be much shorter than the radiative lifetime of the former state. For kinetic temperatures $\gtrsim 20°\text{K}$ this implies that ~90% of the H_2CO molecules along the line of sight will be in the 1_{11} and 1_{10} levels.

The H_2CO projected densities (number density integrated along the line of sight) for two features in the Sgr A spectrum (Fig. 1) were estimated from the relation $T_A = B\eta(T_\mu - T_B)(1 - e^{-\tau})$, where T_A is the antenna temperature of absorption line, T_B the brightness temperature of the background source, η the telescope efficiency, τ the optical depth, and B the beam dilution factor. Analysis of absorption lines has been discussed in detail elsewhere.[7] The integral of the mean optical depth[7] over the linewidth may be expressed as

$$\int \langle \tau \rangle d\nu = (8\pi^3/3hc)\nu |\mu|^2 PNL, \qquad (1)$$

where ν is the microwave frequency, $|\mu|$ the dipole-moment matrix element, and NL the projected density. P is defined by

$$P = \frac{d_n \exp(-E_l/kT_s)[1 - \exp(-h\nu/kT_\mu)]}{1 + d_n \exp(-E_l/kT_s)[1 + \exp(-h\nu/kT_\mu)]}, \qquad (2)$$

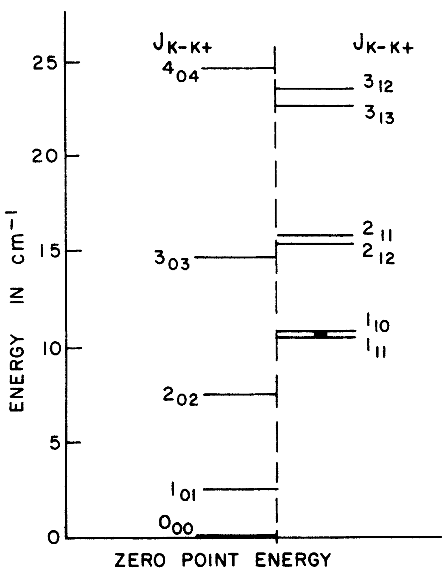

FIG. 2. Lowest energy levels of H_2CO, illustrating the detected interstellar transition.

where d_n is the total degeneracy, E_l the energy of the 1_{11} level, and it is assumed that only 0_{00}, 1_{11}, and 1_{10} states have significant population. As long as $T_\mu \gtrsim 1°K$ it is possible to expand Eq. (2) and express the H_2CO projected density NL directly in terms of T_μ. For $T_S \gtrsim 20°K$, we have $P = 0.45h\nu/kT_\mu$, and we then obtain $NL/T_\mu = 6 \times 10^{13}$ cm^{-2} °K^{-1} for the 40-km/sec feature in Fig. 1 (for which $\Delta\nu = 500$ kHz and $\tau = 0.075$) and $NL/T_\mu = 4\times 10^{12}$ cm^{-2} °K^{-1} for the −50-km/sec line ($\Delta\nu = 65$ kHz and $\tau = 0.038$). For $T_\mu = 10°K$, this implies $NL = 6\times 10^{14}$ cm^{-2} and $NL = 4\times 10^{13}$ cm^{-2} for the two features. In the absence of any pumping effects that might anti-invert the 1_{10} and 1_{11} levels (as in the case of anomalous 18-cm OH absorption[8]) we regard these numbers as approximate lower bounds on the projected densities. If the clouds in which the H_2CO is located are clumpy or if they subtend a solid angle that is smaller than the background source (which is true for OH[9]) then NL must be increased. From our preliminary data reduction we believe that these values for NL/T_μ are representative of the H_2CO features observed against other sources.

In a high-density region ($N_H \gtrsim 10^7$ cm^{-3}), perhaps one associated with an H II region or region of anomalous OH emission, the relative populations among all the levels shown in Fig. 2 may be described by a Boltzmann distribution. For a given optical depth, the projected densities estimated with the Boltzmann distribution are an order of magnitude greater than those calculated from Eq. (1).

The detection of interstellar formaldehyde provides important information about the chemical physics of our galaxy. We now know that polyatomic molecules containing at least two atoms other than hydrogen can form in the interstellar medium. Their formation apparently does not require extremely unusual interstellar conditions since we detected H_2CO in clouds at various distances between earth and the background radio sources in 60% of the cases. Hence large regions of the galaxy may be filled with clouds containing formaldehyde at densities apparently comparable with that of OH. This evidence coupled with the recent discovery of ammonia in the galactic center[10] and water in several sources[11] indicates that processes of interstellar chemical evolution may be much more complex than previously assumed.

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