

# DETECTION OF INTERSTELLAR THIOFORMALDEHYDE

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## Abstract

The  $2_{11} \leftarrow 2_{12}$  transition of thioformaldehyde (HCHS) has been observed in absorption in the direction of Sagittarius B2. For a rest frequency of 3139.38 MHz the peak absorption occurs at a radial velocity of  $60 \pm 4 \text{ km s}^{-1}$ . The half-width of the absorption profile is equivalent to  $20 \text{ km s}^{-1}$  and the column density of HCHS is greater than  $10^{16} \text{ molecules cm}^{-2}$ . Comparison with the  $2_{11} \leftarrow 2_{12}$  absorption of formaldehyde (HCHO) at 15 GHz allows the relative abundance of the two molecular species to be computed as a function of the rotational excitation temperature. For thermal equilibrium the strength of the  $1_{10} \leftarrow 1_{11}$  absorption in Sgr B2 by thioformaldehyde predicted from the  $2_{11} \leftarrow 2_{12}$  HCHS observations is considerably greater than the limits set by a number of observers for the  $1_{10} \leftarrow 1_{11}$  transition at 1046 MHz.

## I. INTRODUCTION

The widespread distribution of formaldehyde (HCHO) and carbon monoxide (CO) in the interstellar medium and the subsequent discovery of CS, the sulphur analogue of CO, in a number of radio sources suggest that thioformaldehyde (HCHS), the sulphur analogue of formaldehyde, may also be present. The microwave spectrum of thioformaldehyde has been observed in the laboratory by Johnson and Powell (1970) and has been the subject of an NBS critical review (Lovas *et al.* 1971).

Evans *et al.* (1970*b*) and Davies *et al.* (1971) searched for the  $1_{10} \leftarrow 1_{11}$  transition of thioformaldehyde in the direction of several strong radio sources. Their searches were unsuccessful and it was concluded that the molecular abundance ratio of HCHS to HCHO was less than the accepted cosmic abundance ratio of sulphur to oxygen (1 : 40). The low limits set for the  $1_{10} \leftarrow 1_{11}$  transition would appear to preclude the possibility of observing the higher *K*-type doubling transitions, provided that there is a thermal distribution of rotational state populations. However, the observed  $2_{11} \leftarrow 2_{12}$  (Evans *et al.* 1970*a*) and  $3_{12} \leftarrow 3_{13}$  (Welch 1970) transitions of formaldehyde do not appear to be consistent with a simple thermal interpretation in this molecule and, with this in mind, it was decided to search for the  $2_{11} \leftarrow 2_{12}$  transition of thioformaldehyde.

## II. OBSERVATIONS

Observations were made with the Parkes 64 m telescope in conjunction with a 9 cm parametric receiver. The adopted rest frequency for the  $2_{11} \leftarrow 2_{12}$  transition of thioformaldehyde was  $3139.38 \pm 0.03 \text{ MHz}$  (Johnson and Powell 1970). The half-power beamwidth of the telescope at the transition frequency was  $6'.4$  arc and the aperture efficiency about 55%.

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The receiver was switched at 19 Hz between two linearly polarized horns, one of which was used as an offset reference horn. Balance noise could be added to the reference input and the receiver gain was monitored by injection of a calibration signal from an argon discharge tube. The overall system noise temperature on cold sky was  $\sim 230$  K. A multichannel recording technique was employed with a set of 64 contiguously spaced filters having a bandwidth of 33.3 kHz, the corresponding resolution in radial velocity being  $3.18 \text{ km s}^{-1}$ .

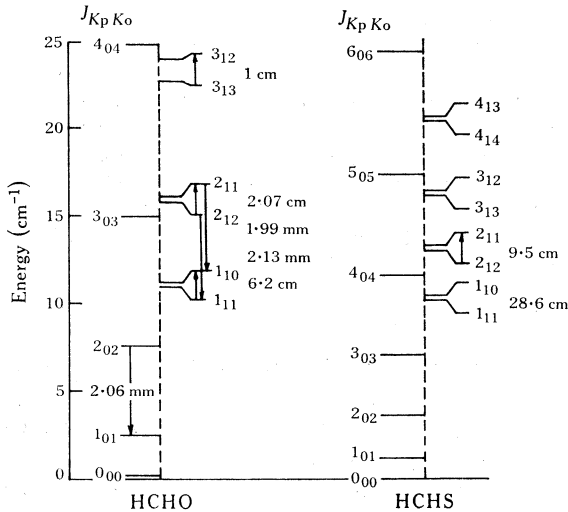


Fig. 1.—Lowest rotational energy levels measured in reciprocal wavelengths for formaldehyde (HCHO) and thioformaldehyde (HCHS). Transitions detected in the interstellar medium are indicated by arrows and their wavelengths are given alongside.

An on-line PDP-9 computer was used to perform the front-end switching and synchronous detection as well as to integrate and calibrate the received signals. The line profile was continuously displayed on an oscilloscope and recorded on tape at the end of each integration period. Before and during each observing period, the H 127 $\alpha$  recombination line at 3172.864 MHz was observed in Orion A and Sgr B2 to test the overall system. Preliminary data reduction was performed with the PDP-9 at the end of each observing session while subsequent reduction was handled by a CDC 3200.

As pointed out by Gardner *et al.* (1971) the telescope gain with respect to frequency is modulated by reflections between vertex and feed platform with a period of 5.7 MHz. To minimize this effect an observation usually consisted of a 15 min integration with the telescope tracking the source, followed by a 15 min reference integration east of the source. By thus maintaining the same zenith angles for both integrations, signal variations due to changes in telescope gain and focus with zenith angle were made identical. A further smoothing of the modulation effect was achieved by averaging several line profiles with different focus settings.

To reduce instrumental effects associated with particular channels, several line profiles whose centre frequency was  $f_0 \pm \Delta f$  ( $\Delta f$  being an integral number of channels) were first averaged, then shifted back by  $\Delta f$  during the data reduction period, and finally averaged again with profiles centred on  $f_0$ .

## III. RESULTS

The lower energy levels of both formaldehyde and thioformaldehyde are shown schematically in Figure 1, with the observed transitions indicated by arrows.

We detected the  $2_{11} \leftarrow 2_{12}$  transition of thioformaldehyde in absorption in the direction of Sgr B2 during two observing periods: 25–27 September and 13–17 December 1971. A line profile taken at the continuum maximum of Sgr B2 with the 33.3 kHz filters and an integration time of 1 hr on source is shown in Figure 2.

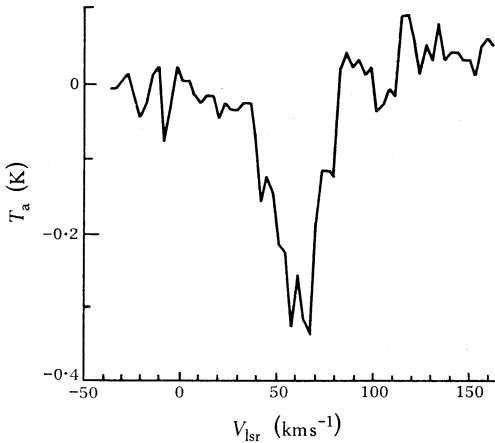


Fig. 2.—Antenna temperature  $T_a$  as a function of radial velocity  $V_{lsr}$  for the  $2_{11} \leftarrow 2_{12}$  transition of thioformaldehyde in Sgr B2. The radial velocity at the peak is  $60 \pm 4 \text{ km s}^{-1}$ . The filter bandwidths were 33.3 kHz and the integration time was 1 hr on source.

The radial velocity at the peak is  $60 \pm 4 \text{ km s}^{-1}$ , which agrees well with the velocities of other molecules detected in Sgr B2. The width of the profile at half-intensity is about  $20 \text{ km s}^{-1}$ . For formaldehyde the peak of the  $1_{10} \leftarrow 1_{11}$  transition is at  $64 \text{ km s}^{-1}$  and the width is about  $25 \text{ km s}^{-1}$  (Gardner and Whiteoak 1970).

TABLE 1  
HCHS  $2_{11} \leftarrow 2_{12}$  ABSORPTION IN SGR B2

Position relative to continuum maximum	Continuum temperature $T_C^*$ (K)	Peak absorption $\Delta T_L^*$ (K)	Integration time (min)
Max.	30	0.33	60
3'N.	24	0.33	60
3'S.	25	0.16	60
6'N.	10	0.25	60
9'N.	5	$< 0.1$	30
9'E.	5	$< 0.1$	30
3'E.	19	$< 0.1$	30
3'W.	23	0.16	45

\* Both  $T_C$  and  $\Delta T_L$  are given as antenna temperatures here while throughout the text main beam brightness temperatures are used, the beam efficiency being taken as 70%.

Table 1 shows measurements made in the vicinity of Sgr B2. The line was detected up to 6' arc north of the continuum maximum and also 3' south and 3' west.

With the limited integration time no line could be detected 3' east, although the continuum intensity there is the same as at 3' north and 3' south. The line : continuum ratio was 0.011 at the continuum maximum and reached a maximum value of 0.025 at the position 6' north.

We have searched for the  $2_{11} \leftarrow 2_{12}$  thioformaldehyde transition in W51, RCW 38, and NGC 2024 without success. Insufficient observing time was spent on Sgr A to establish a meaningful limit on the optical depth of HCHS.

#### IV. DISCUSSION

It is well-known from the general line-formation theory for an ensemble of molecules having a thermal population distribution over the rotational energy levels that, for a rotational absorption line of transition frequency  $\nu_{ul}$  between two rotational states  $u$  (the upper level) and  $l$  (the lower level), the integrated optical depth may be expressed by

$$\int_0^\infty \tau \, d\nu = \frac{8\pi^3}{3hc} |\mu_{ul}|^2 \nu_{ul} \frac{g_u}{g_l} (NL)_l \{1 - \exp(-h\nu_{ul}/kT)\}, \quad (1)$$

where  $T$  is the temperature,  $|\mu_{ul}|^2$  is the dipole matrix element, and  $g_u$  and  $g_l$  are the degeneracies of levels  $u$  and  $l$ . The quantity  $(NL)_l$  is the projected density of the molecular species in the state  $l$  and is related to the total population projected density  $NL$  through

$$\frac{(NL)_l}{g_l} = \frac{NL \exp(-E_l/kT)}{\sum_i g_i \exp(-E_i/kT)}, \quad (2)$$

where  $E_l$  is the energy of the lower level,  $g_i$  the degeneracy of rotational state  $i$ , and  $E_i$  the energy for that state, while the summation is taken over all rotational states.

From equations (1) and (2) the total projected density  $NL$  is given by

$$NL = \frac{3hc \int_0^\infty \tau(\nu) \, d\nu \sum_i g_i \exp(-E_i/kT)}{8\pi^3 |\mu_{ul}|^2 \nu_{ul} g_u \exp(-E_l/kT) \{1 - \exp(-h\nu_{ul}/kT)\}}. \quad (3)$$

Various approximations to this equation have appeared in other discussions of line formation. However, the exact form (3) is used for all calculations presented here, with the minor approximation that the summation is restricted to energies below  $50 \text{ cm}^{-1}$ . This limits the applicability of equation (1) to temperatures much less than 72 K (at which  $kT/hc = 50 \text{ cm}^{-1}$ ). The optical depth  $\tau(\nu)$  is related to the observable brightness temperatures  $\Delta T_L(\nu)$  and  $T_C$  of the absorption line and the background continuum respectively by the usual expression

$$\tau(\nu) = -\ln\{1 - \Delta T_L(\nu)/(T_C + T_{\text{iso}} - T)\}, \quad (4)$$

where  $T_{\text{iso}}$  is the brightness temperature of the isotropic radiation field and  $T$  is the temperature that appears in equation (1). In accordance with the currently accepted view,  $T_{\text{iso}}$  is taken to be 2.7 K. The rotational temperature for a molecular cloud is not directly observable, so  $T$  will be treated as a variable parameter throughout the

discussion. For absorption lines it follows from equation (4) that the inequality

$$0 \leq T < T_c + T_{\text{iso}} - \Delta T_L$$

must apply, so that the range of variation of  $T$  that must be considered is conveniently small in many cases. We shall also assume that the optical-depth line shape is Gaussian.

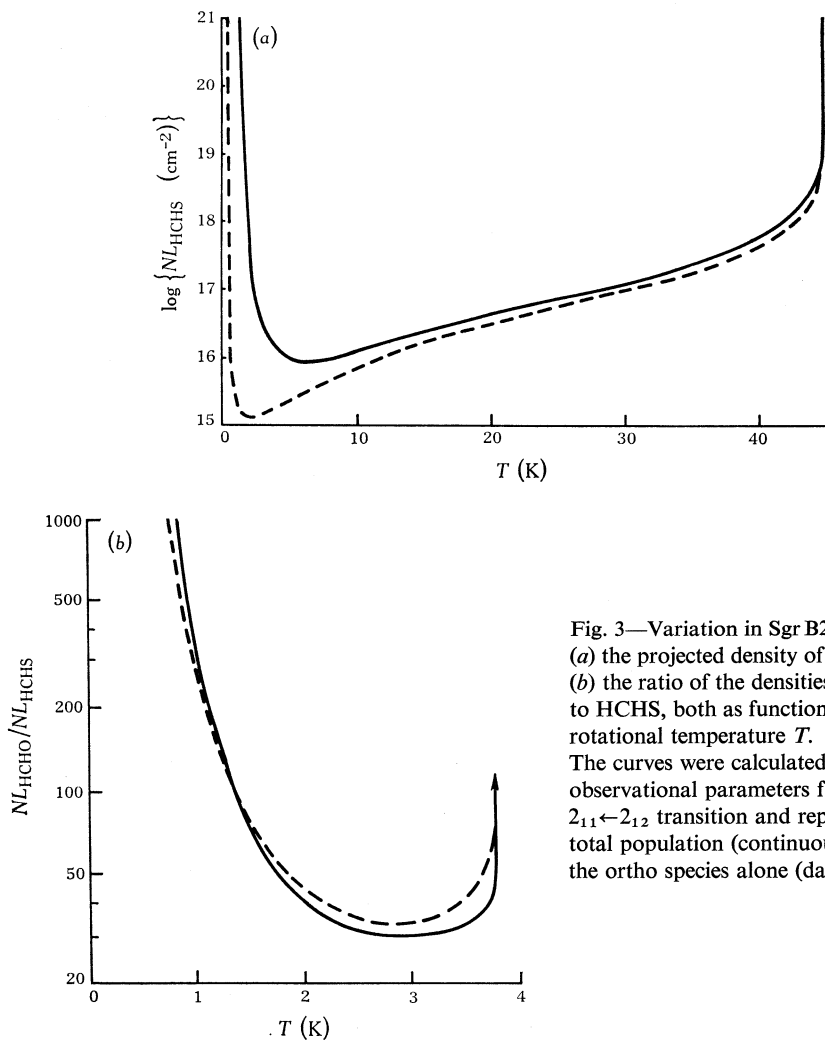


Fig. 3—Variation in Sgr B2 of  
(a) the projected density of HCHS and  
(b) the ratio of the densities of HCHO  
to HCHS, both as functions of  
rotational temperature  $T$ .

The curves were calculated from the observational parameters for the  $2_{11} \leftarrow 2_{12}$  transition and represent the total population (continuous curve) and the ortho species alone (dashed curve).

Figure 3(a) shows the relationship (obtained from equations (3) and (4)) between the projected density and rotational temperature using the HCHS  $2_{11} \leftarrow 2_{12}$  absorption data at the continuum maximum position in Sgr B2 together with molecular constants from Lovas *et al.* (1971). The figure shows projected densities for the ortho species and for the total molecular population (assuming thermal equilibrium between the ortho and para species). The observed transition is from the ortho thioformaldehyde species.

As in the case of formaldehyde, there are no electric dipole transitions from the ortho species manifold to the para species manifold, which has a different hydrogen nuclear spin state. Collisions with other molecules are also thought to be quite inefficient in interchanging molecules between the two manifolds, and so it might be argued that ortho and para nuclear states are distinct chemical species in the interstellar medium and that observation of only one of the states does not convey information regarding the abundance of the other.

In Figure 3(b) the projected density ratios  $NL_{\text{HCHO}}/NL_{\text{HCHS}}$  are shown, the rotational temperatures for the two molecules being assumed equal. The projected density for HCHO as a function of temperature was obtained using observational data for the  $2_{11} \leftarrow 2_{12}$  transition in Sgr B2 from Evans *et al.* (1970a) with molecular constants from Kirchhoff *et al.* (1971). The ratios are found to be essentially equal for the total molecular populations and the ortho species alone. It can be seen that the curve is quite close to the accepted elemental abundance ratio of 40 for rotational temperatures in the range 2–3.5 K. However, on chemical grounds it is likely that such agreement is coincidental.

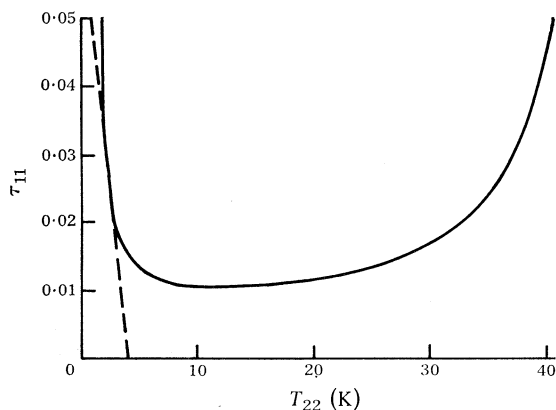


Fig. 4.—Optical depth  $\tau_{11}$  for the HCHS  $1_{10}-1_{11}$  transition in Sgr B2 as a function of the excitation temperature  $T_{22}$  of the observed  $2_{11} \leftarrow 2_{12}$  absorption. The continuous and dashed curves are calculated assuming a simple thermal population distribution and that all millimetre wave transitions are in equilibrium with the 2.7 K isotropic background radiation respectively (see text).

Optical depths  $\tau_{11}$  for the thioformaldehyde  $1_{10}-1_{11}$  transition, calculated from the total projected density curve for the  $2_{11} \leftarrow 2_{12}$  transition given in Figure 3(a), are plotted in Figure 4. The continuous curve shown is based on the assumption of equal rotational temperatures for each transition. The minimum  $\tau_{11}$  of 0.011 is about four times greater than the observational upper limit for Sgr B2 set by Evans *et al.* (1970b) and about three times greater than that set by the work of Davies *et al.* (1971). Therefore the failure to observe the  $1_{10}-1_{11}$  line indicates that the rotational state populations in thioformaldehyde do not follow a thermal law.

Evans *et al.* (1970b) and Davies *et al.* (1971) have computed similar values (within a factor of two) for the  $1_{10}-1_{11}$  absorption of  $\text{H}^{12}\text{CH}^{32}\text{S}$  from the  $1_{10} \leftarrow 1_{11}$  observations of  $\text{H}^{13}\text{CH}^{16}\text{O}$ , adopting the cosmic abundances for  $^{32}\text{S}$ : $^{16}\text{O}$  and  $^{13}\text{C}$ : $^{12}\text{C}$ . The  $\text{H}^{13}\text{CH}^{16}\text{O}$  transition was chosen because it was believed to be free from the effects of high optical depth found in the  $1_{10} \leftarrow 1_{11}$  transition of  $\text{H}^{12}\text{CH}^{16}\text{O}$ .

One plausible systematic deviation from a thermal distribution is the case in which the population ratios between levels connected by millimetre wave electric dipole transitions are in thermal equilibrium with the 2.7 K isotropic background

radiation. The ratios between levels connected by centimetre wave transitions, or no transitions at all, are assumed to be determined by some unspecified process that results in excitation temperatures different from 2.7 K. These latter population ratios are not independent, although the excitation temperatures will generally be different for each pair of levels considered. If an excitation temperature  $T_{22}$  is assumed for the observed  $2_{11} \leftarrow 2_{12}$  doublet of HCHS then the excitation temperature, optical depth, and absorption or emission line brightness temperature for the  $1_{10}-1_{11}$  doublet are directly calculable without further assumption. The dashed line in Figure 4 represents the result of such a calculation. Excitation temperatures greater than 4.01 K in the  $J = 2$  doublet would cause emission rather than absorption in the  $1_{10}-1_{11}$  line, and above 4.05 K there would be a population inversion resulting in maser emission. Strong emission has not been observed during the searches for the  $1_{10}-1_{11}$  transition. It follows that the excitation temperature  $T_{22}$  for the  $J = 2$  doublet must be less than about 4 K if the millimetre radiation equilibrium model is appropriate. If the excitation temperature  $T_{22}$  is below 3.8 K the calculated optical depth for the  $1_{10}-1_{11}$  line exceeds the limits set in the searches for the line in Sgr B2. If the millimetre wave transitions were equilibrated at  $T = 5$  K, inversion of the  $1_{10}-1_{11}$  doublet would occur at  $T_{22} = 7.5$  K.

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