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THE MICROWAVE SPECTRUM OF THE CP RADICAL AND RELATED ASTRONOMICAL SEARCH

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ABSTRACT

The rotational spectrum of the CP radical was detected in the laboratory by using a source-modulated microwave spectrometer combined with a free space absorption cell. The CP radical was produced by a dc–glow discharge in a mixture of PH_3, CH_4, and He. Nineteen lines of five rotational transitions were observed in the frequency region of 95–334 GHz and were least-squares analyzed to determine the molecular constants: the rotational constant, the centrifugal distortion constant, the spin-rotation coupling constant, and hyperfine coupling constants for the phosphorus nucleus. Based on the measured and calculated line frequencies, astronomical searches for the interstellar CP radical were made in Orion-KL, Sgr B2, W51A, TMC-1, and IRC +10216, for which upper limits to the column density were estimated.

Subject headings: interstellar: molecules — laboratory: spectra — line identifications — molecular processes

I. INTRODUCTION

Recently Turner and Bally (1987) and Ziurys (1987) detected the first phosphorus-containing interstellar molecule PN in relatively warm molecular clouds, Orion-KL, W51M, and Sgr B2, and found that its abundance is 10^3–10^4 times higher than that predicted from an ion-molecule reaction scheme by Thorne *et al.* (1984). This is in sharp contrast with the abundance of PO. According to the ion-molecule reactions model, PO is suggested to be the most abundant molecule containing phosphorus in dense molecular clouds (Thorne *et al.* 1984; Thorne, Anicich, and Huntress 1983). However, PO has not yet been detected in space in spite of extensive astronomical searches (Kawaguchi *et al.* 1985; Matthews, Feldman, and Bernath 1987). Upper limits to the column density estimated for various sources suggest that the abundance of PO is a few times less than that of the theoretical prediction. Turner and Bally (1987) proposed a chemical model for production of phosphorus compounds to explain the abundances of PN and PO in space; PN might be formed efficiently by gas-phase reactions between species released from the grain mantles in warm clouds.

We have recently detected successive members of a new sulfur-containing carbon-chain molecule, CCS and C_3S, in the laboratory and then identified them in molecular clouds (Kaifu *et al.* 1987; Saito *et al.* 1987; Yamamoto *et al.* 1987). The high abundance of the carbon-chain molecule C_nS suggests a possibility that other heteroatom-containing carbon-chain families C_nX such as C_nP may exist in space. CP is the first member of a carbon-chain family C_nP. Thorne *et al.* (1984) estimate bond energies of several simple molecules containing phosphorus, reporting that the CP radical has the highest bond energy among them. If the molecule having larger bond strength might be favored in grain vaporization or disruption, CP may have a high abundance in circumstellar envelopes and warm clouds. Any information for simple phosphorus-containing molecules could be helpful for better understanding of phosphorus chemistry in space.

A few high-resolution spectroscopic studies have been made for the CP radical. Herzberg and his collaborators (Herzberg 1930; Barwald, Herzberg, and Herzberg 1934) studied the $B\ ^2\Sigma^+$–$X\ ^2\Sigma^+$ and $B\ ^2\Sigma^+$–$A\ ^2\Pi_i$ transition of CP and determined molecular constants of the ground electronic state. Very recently Ram and Bernath (1987) observed the infrared emission spectrum of the $A\ ^2\Pi_i$–$X\ ^2\Sigma^+$ transition by using a high-resolution Fourier transform spectrometer, and determined detailed and accurate molecular constants for both the states. They produced the CP radical by microwave discharge in a mixture of hydrogen and white phosphorus vapor in a tube coated with a carbon deposit.

II. LABORATORY OBSERVATIONS

A microwave spectrometer at Nagoya University (Yamamoto and Saito 1988) was employed in the laboratory observations. The spectrometer is a 100 kHz source-modulated system covering the frequency region 40–400 GHz, combined with a 2 m long free space absorption cell of a 10 cm outer diameter Pyrex tube. The source radiation above 220 GHz is supplied by commercial multipliers. The frequency region around 140 GHz is covered by a homemade harmonic generator, which is made of a crossed waveguide (WR-15 and WR-8) with a 1N53 mixer diode as a multiplier element. The harmonic generator was driven by an OKAYA klystron 70V10A. An InSb photoconductive detector operated at 4.2 K was used to

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[1] Nobeyama Radio Observatory, a branch of National Astronomical Observatory of Japan, is a facility open to researchers in the field of astronomy.

detect the millimeter-wave power. The absorption cell was kept at about −140° C during the observations.

An initial search was started by using a dc–glow discharge in a mixture of CH_4 and PH_3. The discharge gave strong signals of HCP (Tyler 1964; Johns, Stone, and Winnewisser 1971). We looked for the CP lines in the frequency region of 287 GHz under various conditions, optimized for HCP production or at different mixing ratios of PH_3 to CH_4. However, we could not detect any paramagnetic lines. When we added a large amount of He to the reaction gas mixture, we found a broad paramagnetic line at 286562 MHz by using a CRO display. The paramagnetic line disappeared when the supply of any one of the gases was stopped. The line was found to be resolved into a doublet at a reduced total pressure and to become stronger at a high partial pressure of He. The roughly measured frequencies for the doublet were 286561.7 and 286562.6 MHz, which compare well with the predicted frequencies, 286560.9 and 286563.7 MHz, for the $N = 6$–5 F_1 transition of CP from molecular constants obtained by Ram and Bernath (1987), and from hyperfine coupling constants estimated from those of related free radicals: CN (Dixon and Woods 1977), SiN (Saito, Endo, and Hirota 1983), NO (Kristiansen 1977), and PO (Kawaguchi, Saito, and Hirota 1983). On the basis of these results, we concluded that the observed paramagnetic lines are the hyperfine resolved transitions of CP.

The requirement of a large amount of He suggests that the reaction of CP with itself or other species is very rapid, and inactive He is efficient in keeping CP away from other active species. An optimum condition for the lines was obtained when the partial pressures of CH_4, PH_3, and He were 2, 1, and 50 m torr, respectively, and the discharge current was 600 mA. Figure 1 shows an example of the observed spectrum: the $N = 6$–5 transition at 286 GHz, split into two spin components which consist of hyperfine doublet components due to the phosphorus nucleus. We observed five rotational transitions of $N = 2$–1, 3–2, 5–4, 6–5, and 7–6 in the frequency region 95–334 GHz. Nineteen lines were observed as listed in Table 1. The lowest rotational transition of $N = 1$–0 at 48 GHz could not be observed because of its low intensity. Each line frequency was determined from five pairs of upsweep and downsweep measurements, and the standard deviation of frequencies measured is several to about 20 kHz, depending on the signal-to-noise ratio of the line as given in Table 1.

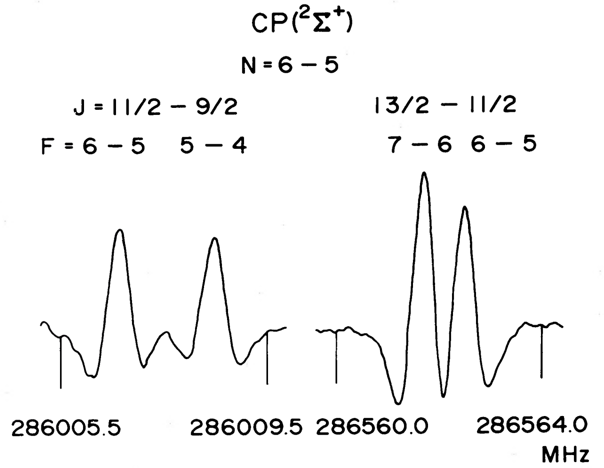

FIG. 1.—$N = 6$–5 transition of the CP radical observed in laboratory. The radical was produced by the dc–glow discharge of 500 mA with a mixture of CH_4 (2 mtorr), PH_3 (6 mtorr), and He (20 mtorr). The integration time was 8 s (40 scans).

The observed spectral lines were analyzed by using a Hamiltonian including molecular rotation, electron-spin rotation interaction, and hyperfine interaction due to the phosphorus nucleus. The rotational constant, centrifugal distortion constant, spin-rotation coupling constant, and magnetic hyperfine coupling constants of the phosphorus have been determined from 19 observed spectral lines by a least-squares fitting program (Saito, Endo, and Hirota 1983), where the matrix elements in Hund's case $b_{\beta J}$ coupling scheme for the Hamiltonian described above are numerically diagonalized and the transition frequencies are calculated. The molecular constants thus derived are listed in Table 2. The standard deviation of the fit is 0.023 MHz, which is of the same order of magnitude as the frequency measurement error, as shown in Table 1.

III. ASTRONOMICAL SEARCH

We carried out astronomical searches in 1987 August and 1988 January by using the 45 m radio telescope of Nobeyama Radio Observatory (NRO). The spectral lines searched were the $N = 1$–0 transition at 48 GHz and the $N = 2$–1 transition at 96 GHz. The front end used for the 48 GHz region was a SIS mixer with a bandwidth of 800 MHz, and that for the 96 GHz region was a cooled Schottky-barrier diode mixer with a bandwidth of 500 MHz. Both transitions were searched for simultaneously by using a polarization beam splitter. We used two types of acousto-optical spectrometers, eight AOS-W (250 kHz resolution, 250 MHz bandwidth, and 2000 channel output each) and eight AOS-H (37 kHz resolution, 40 MHz bandwidth, and 2000 channel output each), in parallel and covered the frequency regions 47.5–48.3 GHz and 95.3–95.8 GHz. The system temperatures were 300–450 K for the SIS receiver at 48 GHz, after correction for the image rejection ratio (typically 6 dB), and 400–450 K at 96 GHz. Antenna temperatures, T_A^*, are corrected for the atmospheric attenuation and are also corrected for the image rejection ratio for the 48 GHz data. The beam size and the main-beam efficiencies at 48 and 96 GHz are about 40″ and 20″ and 0.8 and 0.4, respectively. The pointing of the antenna was checked every 1.5–2 hr by observing the SiO masers of nearby stars or those associated with the source itself.

We observed three massive star-forming regions [Orion-KL, Sgr B2(NW), and W51A], a cold dark molecular cloud (TMC-1), and a carbon-rich star (IRC +10216). We observed no signals for the CP spectral lines as summarized in Table 3. Figure 2 shows the spectrum observed in the frequency region around 95.7 GHz toward Orion-KL, with vertical bars indicating the line frequencies of CP. A line is recognized at 95710.73 MHz, near to the laboratory observed frequency, 95710.245(22) MHz (see Table 1), for the $N = 2$–1, $J = 5/2$–$3/2$, $F = 3$–2 transition of CP. However, this line could not be assigned to the CP line because no feature was detected at the frequency of 95712.631 MHz for the $F = 2$–1 component of the $N = 2$–1, $J = 5/2$–$3/2$ transition whose intensity was estimated to be 64% of that for the $F = 3$–2 component. All lines detected from Orion-KL are listed in Table 4, where lines observed in the lower sideband are included with their intensities corrected by the image rejection ratio given above. Twenty-two lines are newly identified, and eight lines are left unidentified in this observation. In Table 4 lower sideband

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TABLE 1

OBSERVED ROTATIONAL TRANSITIONS OF CP($^2\Sigma^+$)(MHz)

N'–N	J'–J	F'–F	$\nu_{\rm obs}$[a]	$\nu_{\rm obs} - \nu_{\rm calc}$[b]
1–0....................	3/2–1/2	2–1	47982.893[c]	...
		1–0	47979.906[c]	...
		1–1	48112.451[c]	...
	1/2–1/2	1–1	47256.884[c]	...
		1–0	47124.339[c]	...
		0–1	47011.781[c]	...
2–1....................	5/2–3/2	3–2	95710.245(22)	−0.003
		2–1	95712.631(15)	−0.016
	3/2–1/2	2–1	95164.158(23)	0.003
		1–0	95235.839(23)	0.007
3–2....................	7/2–5/2	4–3	143429.958(12)	0.026
		3–2	143431.758(21)	0.029
	5/2–3/2	3–2	142878.641(16)	−0.018
		2–1	142891.958(25)	−0.036
5–4....................	11/2–9/2	6–5	238855.959(8)	−0.024
		5–4	238856.932(4)	−0.005
	9/2–7/2	5–4	238301.574(15)	0.016
		4–3	238304.519(10)	−0.005
6–5....................	13/2–11/2	7–6	286561.701(10)	−0.023
		6–5	286562.478(8)	0.030
	11/2–9/2	6–5	286006.708(2)	0.025
		5–4	286008.540(5)	0.006
7–6....................	15/2–13/2	8–7 7–6	334261.819(15)[d]	−0.016
	13/2–11/2	7–6	333706.119(20)	−0.022
		6–5	333707.425(26)	0.021

[a] Values in parentheses denote 1 standard deviation of the frequency measurements and apply to the last digits of the frequencies.

[b] Calculated frequencies were obtained by using molecular constants given in Table 2. The standard deviation of the fit is 0.023 MHz.

[c] Calculated frequencies.

[d] Unresolved line. The calculated frequency is an average of the component frequencies weighted by their relative intensities.

frequencies are also given for the unidentified lines because no attempt was made to distinguish between the upper sideband and lower sideband frequencies by making another observation with a frequency offset. Identified lines in Sgr B2, W51, and IRC +10216 are summarized in Table 5.

Most of the lines given in Table 4 and Table 5 are newly identified spectral lines. There are some points to be noted: (1) We identified for the first time two CH_3OH lines in the $v_t = 2$ state, which were assigned referring to Herbst *et al.* (1984). Details concerning these lines will be reported in a separate paper (Ohishi *et al.* 1988*b*). (2) The C_4H radical was for the first time detected definitely in Sgr B2. Cummins, Linke, and Thaddeus (1986) made a spectral survey toward Sgr B2 and found marginal signals, which seemed to be spectral lines of the C_4H radical, at about 85.6 GHz, but obtained no features corresponding to the C_4H radical at higher frequencies. The spectral lines at 47.6 GHz observed in this study correspond clearly to the fine structure of the $N = 5$–4 transition for C_4H (see Table 5), indicating that the existence of the C_4H radical in Sgr B2 is unambiguous. (3) Finally, we note that the $16_{2,14}$–$16_{1,15}$ transition of $(CH_3)_2O$ in Orion-KL is identified on the basis of calculated frequencies from the molecular constants given by Lovas, Lutz, and Dreizler (1979).

TABLE 2

MOLECULAR CONSTANTS OF THE CP($^2\Sigma^+$) RADICAL (MHz)[a]

Constant	Microwave[b]	FTIR[c]
D_0	23859.9193(59)	23859.930(198)
D_0	0.039892(79)	0.039793(75)
γ_0	556.639(50)	555.93(46)
b_F	−132.46(87)	...
c	454.02(56)	...

[a] Values in parentheses denote 3 times the standard deviation and apply to the last digits of the constants.

[b] Present study.

[c] Ram and Bernath 1987.

IV. DISCUSSIONS

a) Molecular Constants

The observed molecular constants are compared in Table 2 with the values reported by Ram and Bernath (1987) from Fourier transform infrared (FTIR) spectroscopy. The rotational constant, centrifugal distortion constant, and spin-rotation coupling constant agree very well within the standard errors of their result. However, the present values of the rotational constant and the spin-rotation coupling constant are more precise than their corresponding values.

The hyperfine coupling constants of the CP radical have been determined for the first time. The spin density and the *s* character of the unpaired electron orbitals on the P atom are derived from the hyperfine coupling constants, when compared with those of the phosphorus atom given by Morton and Preston (1978). If the angular dependent factor $\langle 3\cos^2\theta - 1\rangle_s$ in the *c* constant (Frosch and Foley 1952) is replaced by 4/5 as

TABLE 3

Astronomical Search for the CP Radical

Source	α(1950.0)	δ(1950.0)	$T_A^{*\,a}$ (mK)	$T_A^{*\,b}$ (mK)	Δv (km s^{-1})	T_{ex} (K)	N^c (cm^{-2})
Orion-KL	$05^h32^m46^s.9$	$-5°24'23''$	$<8^d$	$<9^d$	15	100^e	$<1 \times 10^{14}$
Sgr B2 (NW)	17 44 6.6	−28 21 20	$<6^d$	$<6^d$	20	50^e	$<5 \times 10^{13}$
W51A	19 21 26.2	14 24 43.6	$<13^d$	$<10^d$	27	50^f	$<1 \times 10^{14}$
TMC-1	04 38 38.6	25 35 45	$<24^g$	$<40^g$	0.6	5^h	$<1 \times 10^{12}$
IRC +10216	09 45 15.0	13 30 45.0	$<10^d$	$<12^d$	30	25^e	$<9 \times 10^{13}$

[a] 3 σ noise averaged over the expected line width in the 48 GHz region.

[b] 3 σ noise averaged over the expected line width in the 96 GHz region.

[c] Upper limits to the column density of CP in TMC-1 are calculated from T_A^* at 48 GHz; upper limits to the column density in other sources are calculated from T_A^* at 96 GHz.

[d] From AOS-W data.

[e] Ohishi *et al.* 1988*a*.

[f] Jaffe, Becklin, and Hildebrand 1984.

[g] From AOS-H data.

[h] Yamamoto *et al.* 1987.

calculated for a p_σ orbital, the observed c-value gives an estimate for the spin density on the P atom of 41.3%. On the other hand, the s character calculated from the observed b_F value is very small, −0.01%. As a result, the unpaired electron orbital around the P atom consists mainly of $3p_\sigma$. The obtained spin density and s character are compared with the corresponding values of the related radicals: the spin density of 42.0% and the s character of −0.9% for CN (Dixon and Woods 1977), and 65.6% and 3.3% for SiN (Saito, Endo, and Hirota 1983).

b) Column Density

Since no spectral features of the CP radical have been identified for five astronomical sources, the upper limits to the column density of the CP radical are estimated for each source on the assumptions that the spectral lines used are optically thin, the level populations are in local thermal equilibrium with appropriate excitation temperatures, and the clouds observed fill the antenna beam in each case. The dipole moment of CP has recently been estimated to be 0.86 ± 0.01 debye by an elaborate *ab initio* calculation (Rohlfing and Almlof 1988). No experimentally determined values are available. Upper limits are calculated for each source from the observed upper limits to T_A^* in the frequency region of the $N = 1\text{–}0$ transition, the estimated T_{ex} and Δv listed in Table 3. The results are also given in Table 3.

The upper limit to the column density of CP obtained in this study is 1×10^{12} cm^{-2} for TMC-1, which is 200 times lower than that of CN in TMC-1 (Irvine, Goldsmith, and Hjalmarson 1987). The cosmic abundance ratio between nitrogen and phosphorus is about 390. A much deeper search for CP is necessary for detection of CP or a correct estimation of its upper limit in the dark molecular cloud.

The upper limits to the column density of CP in warm molecular clouds and a circumstellar envelope range from

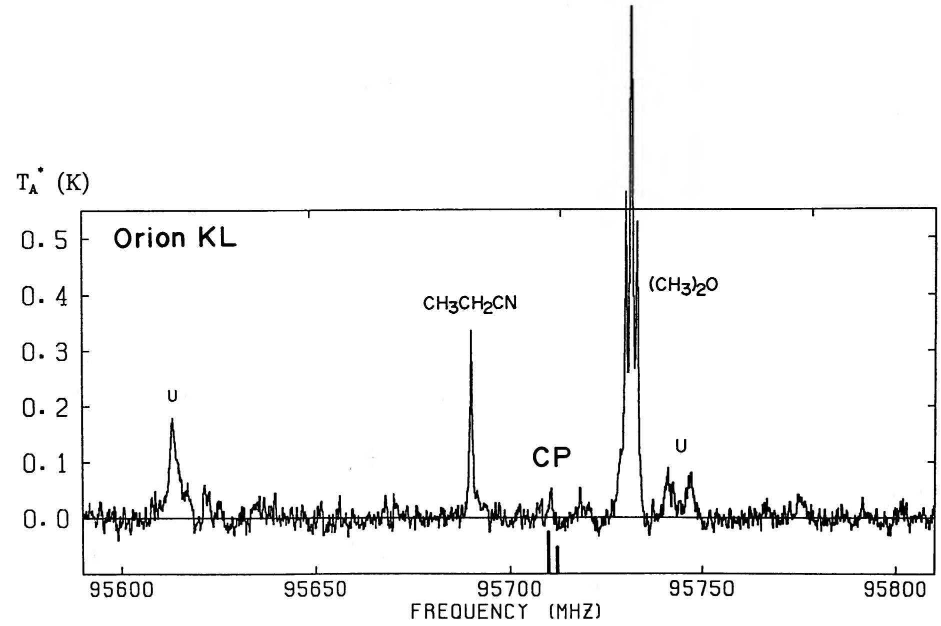

FIG. 2.—A result of an interstellar CP search in the frequency region around 95.7 GHz toward Orion-KL (R.A. = $05^h32^m46^s.9$, decl. = $-5°24'23''$ [1950]) with AOS-W (250 kHz resolution). Vertical bars indicate the expected hyperfine doublet of the $N = 2\text{–}1$, $J = 5/2\text{–}3/2$ transition of CP. A line found at 95710.73 MHz could not be assigned to the $N = 2\text{–}1$, $J = 5/2\text{–}3/2$, $F = 3\text{–}2$ transition of CP (see text).

TABLE 4

OBSERVED SPECTRAL LINES IN ORION-KL

Frequency[a] (MHz)	T_A^* (K)	Δv (km s^{-1})	Identification
		Lower Sideband	
44597.08	0.31	13.22	C_2H_5CN, 5_{05}–4_{04}[b]
44731.19	0.23	9.60	C_2H_5CN, 5_{24}–4_{23}[b]
44878.89	0.30	...	C_2H_5CN, 5_{23}–4_{22}[b, c]
44956.27	0.85	2.98	CH_3OH, $v_t = 1$, 2_0–3_1 E[b]
		Upper Sideband	
47534.18	0.25	3.15	HCO_2CH_3, 4_{04}–3_{03} E[b]
47536.99	0.23	3.59	HCO_2CH_3, 4_{04}–3_{03} A[b]
47660.99	0.08	5.66	SO_2, $31_{5,27}$–$30_{6,24}$[b]
47674.92	0.09	2.67	$(CH_3)_2O$, 1_{11}–0_{00}[b]
47751.89	0.13	21.91	Unidentified[d]
(45048.11)	(0.55)	(23.23)	
47766.54	0.10	22.75	Unidentified[d]
(45033.46)	(0.42)	(23.94)	
47913.90	1.15	21.26	SO_2, $14_{2,12}$–$13_{3,11}$[b]
47927.43	0.06	3.09	HC_5N, $J = 18$–17[b]
47935.51	0.04	18.70	Unidentified[d]
(44864.49)	(0.17)	(19.98)	
48120.94	0.39	13.62	SO_2, $21_{2,20}$–$20_{3,17}$[b]
48155.94	0.93	23.58	H51α[b]
48175.36	0.12	14.22	He51α[b]
48177.40	0.03	7.69	CH_3OH, $v_t = 2$, 1_0–0_0 E[b]
48192.47	0.06	3.56	CH_3OH, $v_t = 2$, 1_0–0_0 A^+[b]
48207.28	0.58	4.43	$C^{34}S$, $J = 1$–0
48248.01	0.23	3.79	CH_3OH, $v_t = 1$, 1_0–0_0 E[b]
48257.71	0.09	4.01	CH_3OH, $v_t = 1$, 1_0–0_0 A^+[b]
48284.76	2.92	3.63	H_2CO, 4_{13}–4_{14}
48292.28	0.06	21.44	Unidentified[d]
(44507.72)	(0.25)	(23.26)	
95443.56	0.99	13.09	C_2H_5CN, $11_{1,11}$–$10_{1,10}$
95503.45	0.07	13.70	C_2H_5CN, $14_{2,13}$–$14_{1,14}$[b]
95553.69	0.16	3.07	$(CH_3)_2O$, 14_{78}–15_{69}[b]
95557.17	0.13	4.53	$(CH_3)_2O$, 14_{77}–$15_{6,10}$[b]
95613.02	0.18	7.96	Unidentified
95690.02	0.34	2.05	C_2H_5CN, 3_{22}–2_{21}[b]
95710.73	0.05	2.25	Unidentified
95730.40	0.58	2.47	$(CH_3)_2O$, $16_{2,14}$–$16_{1,15}$[b]
95731.83	1.14	2.38	
95733.38	0.53	1.66	
95741.28	0.09	7.58	Unidentified
95747.23	0.08	6.18	Unidentified

[a] Frequencies of the unidentified lines are given for $V_{LSR} = 9.0$ km s^{-1}.

[b] Newly identified lines.

[c] Blended with an SO_2 line.

[d] Observed frequencies, antenna temperatures, and line widths in the lower sideband are given in parentheses.

TABLE 5

IDENTIFIED SPECTRAL LINES IN SAGITTARIUS B2, W51, AND IRC +10216

Frequency (MHz)	T_A^* (K)	Δv (km s^{-1})	Identification
		Sgr B2	
47534.70..........	0.15	13.66	HCO_2CH_3, 4_{04}–3_{03} E
47536.49..........	0.16	15.06	HCO_2CH_3, 4_{04}–3_{03} A
47564.62..........	0.10	15.65	C_4H, $N = 5$–4, $J = 11/2$–9/2
47603.35..........	0.09	25.80	C_4H, $N = 5$–4, $J = 9/2$–7/2
47672.76..........	0.05	24.36	$(CH_3)_2O$, 1_{11}–0_{00}
47745.33..........	0.06	37.78	CH_3CHO, 1_{10}–1_{01} E
47819.47..........	0.05	51.30	CH_3CHO, 1_{10}–1_{01} A
47913.90..........	0.06	40.73	SO_2, $14_{2,12}$–$13_{3,11}$
47925.41..........	0.27	24.42	HC_5N, $J = 18$–17
48152.62..........	0.07	28.87	H51α
48205.11..........	0.50	28.93	$C^{34}S$, $J = 1$–0
48285.90..........	0.09	24.37	H_2CO, 4_{13}–4_{14}
		W51	
47913.02..........	0.32	26.30	SO_2, $14_{2,12}$–$13_{3,11}$
48119.66..........	0.04	13.07	SO_2, $21_{2,20}$–$20_{3,17}$
48153.13..........	0.85	27.93	H51α
48173.56..........	0.06	15.88	He51α
48205.51..........	0.98	9.06	$C^{34}S$, $J = 1$–0
48248.83..........	0.06	8.10	CH_3OH, $v_t = 1$, 1_0–0_0 E
48257.70..........	0.07	14.30	CH_3OH, $v_t = 1$, 1_0–0_0 A^+
48283.98..........	0.22	8.10	H_2CO, 4_{13}–4_{14}
95729.50..........	0.12	13.61	$(CH_3)_2O$, $16_{2,14}$–$16_{1,15}$
		IRC +10216	
45262.90[a].........	0.85	28.33	HC_5N, $J = 17$–16
47564.88..........	0.14	15.36	C_4H, $N = 5$–4, $J = 11/2$–9/2
47604.94..........	0.14	24.06	C_4H, $N = 5$–4, $J = 9/2$–7/2
47925.48..........	0.32	27.30	HC_5N, $J = 18$–17
48205.47..........	0.10	25.77	$C^{34}S$, $J = 1$–0
95579.4..........	0.48	23.90	C_2Si, 4_{22}–3_{21}

[a] Observed in the lower sideband.

8×10^{13} to 2×10^{14} cm^{-2}. The present upper limits are not satisfactory when compared with those of PN (Turner and Bally 1987; Ziurys 1987) because the dipole moment of CP is nearly one-third of that for PN (2.7481 debye; Wyse, Manson, and Gordy 1972) and one rotational transition of CP resolves into four fine and hyperfine components. The deepest search was that for Orion-KL, where the upper limit to the column density of CP is 3 times as high as that of PN. Turner and Bally (1987) proposed a chemical model for the production of PN by a combination of grain disruption and gas-phase reactions. If CH_4 is generated in high abundance through grain disruption, a similar chemical model could be applicable to the production of CP in warm molecular clouds (Thorne *et al.* 1984). The abundance of CP can be at most similar to that of PN even in the most favorable case. Therefore, a much deeper search for CP is essential to clarify phosphorus chemistry in warm molecular clouds.

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