

## INFRARED SPECTRA OF HOT HF AND DF

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### ABSTRACT

New Fourier transform emission measurements were obtained for HF and DF at a temperature of 2300 °C. Both pure rotation and vibration-rotation lines were measured with a precision of about 0.0005 cm<sup>-1</sup>. These new lines were combined with previously measured data to give improved rotational constants for the vibrational levels  $v = 0-5$ . The HF molecule is the most convenient monitor of <sup>19</sup>F abundances in cool stars.

*Subject headings:* line: identification — methods: laboratory — molecular processes — stars: abundances

### 1. INTRODUCTION

The element fluorine is difficult to detect in extraterrestrial sources. The <sup>19</sup>F nucleus is easily destroyed by nucleosynthetic reactions in stellar interiors so its abundance is low. The accepted cosmic abundance of 4.48 (on the log  $N_H = 12$  scale) is determined from meteorites (Anders & Grevesse 1989). The detection of fluorine is also difficult because most of the atomic lines, including the resonance lines near 955 Å, are found in the vacuum ultraviolet region (Kelly 1987). Some forbidden transitions of highly ionized F (e.g., [F IV]) have been identified in the solar corona or in planetary nebulae (Aller & Czyzak 1983). However such transitions provide abundance estimates of dubious reliability.

The vibration-rotation transitions of HF near 2.5 μm are the most convenient and reliable lines for F abundance determinations. The pure rotation (Wallace, Livingston, & Bernath 1994) and vibration-rotation lines (Hall & Noyes 1969; Wallace & Livingston 1992) of HF have been detected in sunspots. The vibration-rotation HF lines have also been seen in the atmosphere of Venus (Connes et al. 1967) and in α Ori (Spinrad et al. 1971). In our own Earth's atmosphere these lines appear as the result of the decomposition of chlorofluorocarbons in the stratosphere (Wallace & Livingston 1991).

Apart from HF the only other F containing molecule found in extraterrestrial sources is AlF. The millimeter wave lines of AlF were detected in the circumstellar shell of the carbon star IRC+ 10216 by Cernicharo & Guélin (1987). This surprising discovery was recently confirmed by Ziurys, Apponi, & Phillips (1994). Evidently F abundances are abnormally high in IRC +10216.

Recently the HF vibration-rotation lines were used by Jorissen, Smith, & Lambert (1992) to measure <sup>19</sup>F abundances in a large sample of cool stars. They found that AGB stars have up to 30 times the solar abundance of <sup>19</sup>F, suggesting that <sup>19</sup>F is

synthesized in He-burning shells. The origin of <sup>19</sup>F in our Galaxy is still a matter of dispute and Woosley & Haxton (1988) suggest that it is made in Type II supernovas.

Laboratory measurements of hot HF at 1000–1300°C have been published (LeBlanc, White, & Bernath 1994) but this temperature is still too low for many astronomical applications. The HF molecule can be detected at temperatures in excess of 3000°C in sunspots and stellar atmospheres. Many HF lines identified in these sources have not been measured in laboratory. In addition HF is so light that large centrifugal distortion effects make the extrapolation of high- $J$  line positions from known low- $J$  line positions unreliable. During the course of some unsuccessful experiments on NiF we detected infrared emission from HF and DF impurities at 2300°C. We have combined these new data with previous measurements, and this paper reports on our analysis.

There have been previous measurements of hot HF, most notably recorded from an H<sub>2</sub> + F<sub>2</sub> flame (Mann et al. 1961) but the line positions have an accuracy of about 0.1 cm<sup>-1</sup>. Sen Gupta, Das, & Rao (1979) measured some HF and DF laser lines with an accuracy of about 0.0005 cm<sup>-1</sup> but the data set is relatively limited. Older room temperature DF measurements were made by Spanbauer, Rao, & Jones (1965) and DeLucia, Helminger, & Gordy (1971). Previous HF measurements were reviewed in recent papers (LeBlanc et al. 1994; Hedderich, Walker, & Bernath 1991), and the references will not be cited again here.

A global analysis of HF and DF data by fitting with a parameterized potential function was carried out by Coxon & Hagi-georiou in 1990. This analysis included data on very high vibrational levels  $v = 7-19$  for HF (Di Lonardo & Douglas 1973) and  $v = 9-26$  for DF, obtained from vacuum ultraviolet emission spectra of the B<sup>1</sup>Σ<sup>+</sup>–X<sup>1</sup>Σ<sup>+</sup> electronic transition. Recent calculations of the Einstein  $A$ -values (Zemke et al. 1991) and the dipole moment function (Barnes, Gough, & Stoer 1994) of HF have also been published.

### 2. EXPERIMENTAL

The spectra of HF and DF have been observed over the 40–4600 cm<sup>-1</sup> region in three different experiments carried out at the National Solar Observatory, at the University of Waterloo, and at the National Research Council of Canada.

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### 2.1. National Solar Observatory Measurements

The infrared emission bands of HF and DF were observed at high temperature during a search for NiF emission bands using a commercial carbon tube furnace. The experiment was intended to produce NiF bands by melting Ni in the furnace in the presence of  $\text{CF}_4$  at a temperature of  $2300^\circ\text{C}$ . About 100 torr of He was also present in the furnace as a buffer gas. The spectra observed in this experiment were very rich with strong pure rotation and vibration-rotation bands of HF (Fig. 1) and DF as well as vibration-rotation bands of CO and CS (Ram, Bernath, & Davis 1995).

The emission from the furnace was observed with the 1 m Fourier transform spectrometer associated with the McMath-Pierce solar telescope of the National Solar Observatory at Kitt Peak. The spectrometer was operated with a KCl beam splitter, InAs filters and Si:As detectors to cover the  $550\text{--}2800\text{ cm}^{-1}$  region. A total of five scans were co-added in 13 minutes of integration at a resolution of  $0.01\text{ cm}^{-1}$ . The strongest pure rotational HF lines in our spectra are observed with a signal-to-noise ratio of more than 50.

The vibration-rotation measurements of HF and DF used InSb detectors and a Ge filter to cover the  $1800\text{--}5500\text{ cm}^{-1}$  region. In this case three scans were co-added in 8 minutes at a resolution of  $0.02\text{ cm}^{-1}$ . The width of the HF and DF molecular lines are not constant over the entire spectral range and the low  $J$  lines are self-absorbed. Therefore the line positions of the lower  $J$  transitions have been taken from the previous measurements. The precision of measurement for the sharp and unblended transitions is expected to be better than  $\pm 0.0005\text{ cm}^{-1}$ .

### 2.2. University of Waterloo Measurements

The spectra at the University of Waterloo were recorded using the Bruker IFS 120 HR Fourier transform spectrometer using the experimental arrangement described elsewhere (White, Dulick, & Bernath 1993). Briefly, a carbon boat was loaded with  $\text{CaF}_2$  solid and placed in a mullite tube closed at both ends with KRS-5 windows. The spectrometer was equipped with a KBr beam splitter. The aim of the experiment was to record a spectrum of gaseous  $\text{CaF}_2$ . Although  $\text{CaF}_2$  was not detected, emission spectra of CaF (Charron et al. 1995), BF (Zhang et al. 1995), and DF were recorded. Approximately 10 torr of  $\text{D}_2$  gas was added to the tube at a temperature of about  $1600^\circ\text{C}$  to form DF. For the vibration-rotation bands, 20 scans were co-added at a resolution of  $0.02\text{ cm}^{-1}$  resolution, and the spectra were recorded using an InSb detector. The pure rotational spectra were recorded in two experiments. For the spectra below  $300\text{ cm}^{-1}$ , 20 scans were co-added at  $0.02\text{ cm}^{-1}$  with a bolometer detector and a mylar beam splitter. For  $350\text{--}700\text{ cm}^{-1}$  region, 10 scans were co-added at  $0.02\text{ cm}^{-1}$  resolution and the spectra were recorded using a Si:B detector. The spectra were calibrated using the previous measurements of HF by LeBlanc et al. (1994) and the accuracy of measurements are expected to be about  $\pm 0.0005\text{ cm}^{-1}$ .

### 2.3. National Research Council of Canada Measurements

The pure rotation and vibration-rotation absorption lines of DF were measured in the Herzberg Institute of Astrophysics using a modified Bomem DA3.002 Fourier transform spectrometer (Johns 1987). For the pure rotational transitions, the DF sample was introduced in a 11 cm long cell at a pressure of about 110 mtorr. The absorption spectra were recorded at  $0.002\text{ cm}^{-1}$  resolution using a liquid He cooled Ge bolometer.

The spectra of the fundamental band of DF were recorded using the same spectrometer and a  $\text{CaF}_2$  beam splitter. The InSb detector had a cold  $4\text{ }\mu\text{m}$  short pass filter mounted in the dewar, which, together with a room temperature  $3\text{ }\mu\text{m}$  long pass filter, defined the optical band pass from  $2500\text{--}3300\text{ cm}^{-1}$ . Sixteen co-added scans gave spectra with good S/N. The sample was contained in a 50 cm multiple traversal cell of the type first described by White (1942) and which was set for the minimum four transits to give a nominal path length of 2 m. Altogether three spectra were recorded. In the first, the cell contained only a trace of DF but also a trace of methane for calibration with the F2 component of  $P(7)$  in the  $\nu_3$  band at  $2947.91211\text{ cm}^{-1}$  (Knight et al. 1980). In the other two the DF pressure was 1.5 and 3.0 torr, respectively, allowing observation of lines up to  $R(12)$  and  $P(13)$ . The residuals from the fit to equation (1) (see below) indicate that the precision of measurements was of the order of  $\pm 0.00005\text{ cm}^{-1}$ . The accuracy is, of course, somewhat lower.

## 3. RESULTS AND DISCUSSION

The line positions were extracted from the Kitt Peak and Waterloo spectra using a data reduction program called PC-DECOMP developed by J. Brault. The peak positions were determined by fitting a Voigt line shape function to each spectral feature. The new HF spectra were calibrated using the HF line positions reported by LeBlanc et al. (1994). The Waterloo DF vibration-rotation emission lines were calibrated using the ab-

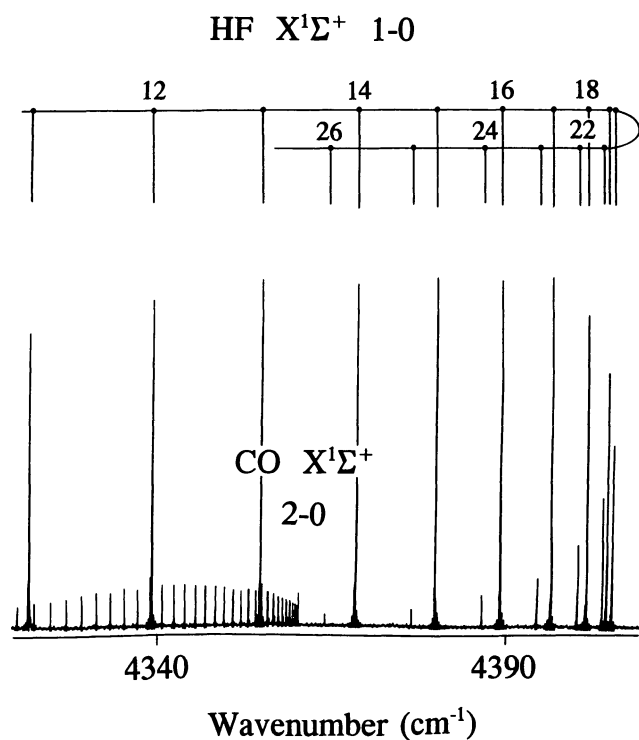


FIG. 1.—Part of the spectrum showing the  $R$  head of the  $1\text{--}0$  vibration-rotation band of HF. The  $R$  head of the  $2\text{--}0$  vibration-rotation band of CO has also been marked.

TABLE 1  
LINE POSITIONS (IN  $\text{cm}^{-1}$ ) OF THE HIGH  $J$  PURE ROTATIONAL LINES OF HF<sup>a</sup>

$J''$	OBS	O—C	$J''$	OBS	O—C	$J''$	OBS	O—C	$J''$	OBS	O—C
$v = 0$											
27 .....	980.58370	99	29	1026.06399	2	31	1067.13753	-38	33	1103.69963	-120
28 .....	1003.86718	36	30	1047.15883	-7	32	1085.98816	-64	34	1120.26465	0
$v = 1$											
22 .....	815.53356	89	26	918.54337	-11	29	985.10526	-10	32	1041.97689	48
23 .....	842.75135	46	27	941.78139	-22	30	1005.15850	7	33	1058.71676	-49
24 .....	869.00760	30	28	963.97457	0	31	1024.11993	25	34	1074.33221	4
25 .....	894.27869	-1									
$v = 2$											
13 .....	511.40203	180	18	670.36032	16	23	809.34869	-13	28	924.91981	-14
14 .....	544.59445	104	19	699.87946	17	24	834.43023	-13	29	944.98541	-23
15 .....	577.12180	17	20	728.56627	23	25	858.54898	-18	31	981.93152	28
16 .....	608.94887	33	21	756.39145	10	26	881.68349	-9	32	998.78249	-8
17 .....	640.03988	65	22	783.32767	4	27	903.81340	-5			
$v = 3$											
14 .....	523.22033	-13	18	643.75983	-21	22	751.79253	0	26	845.52163	47
15 .....	554.41615	-11	19	672.01718	19	23	776.62827	22	27	866.54127	-6
16 .....	584.92745	3	20	699.46074	41	24	800.54360	34	28	886.55639	31
17 .....	614.71996	30	21	726.06171	41	25	823.51454	-39	29	905.54697	-26
$v = 4$											
15 .....	532.17449	142	17	589.89959	-75	19	644.68549	45	21	696.28180	-29
16 .....	561.39016	175	18	617.67742	112	20	670.89627	-28			

<sup>a</sup> National Solar Observatory measurements.

TABLE 2  
LINE POSITIONS (IN  $\text{cm}^{-1}$ ) IN THE VIBRATION-ROTATION BANDS OF HF<sup>a</sup>

LINE	OBS	O-C	LINE	OBS	O-C	LINE	OBS	O-C	LINE	OBS	O-C
1-0											
R(17)	4396.17661	120	R(22)	4399.96736	-26	P(19)	2978.25993	136	P(24)	2674.52490	-48
R(18)	4401.25544	41	R(23)	4394.21427	11	P(20)	2918.27442	75	P(25)	2612.89090	-26
R(19)	4404.18235	2	R(24)	4386.28323	-34	P(21)	2857.85601	22	P(26)	2551.07579	-10
R(20)	4404.94794	5	R(25)	4376.17732	16	P(22)	2797.05753	-3	P(27)	2489.12609	-3
R(21)	4403.54427	-35	R(26)	4363.89811	4	P(23)	2735.93044	-16	P(28)	2427.08679	-10
2-1											
R(12)	4150.84558	156	R(18)	4208.43735	-29	P(15)	3067.19327	142	P(21)	2724.08059	-114
R(13)	4165.55980	90	R(19)	4210.75635	40	P(16)	3011.42992	57	P(23)	2606.12848	-58
R(14)	4178.25404	40	R(20)	4210.95978	57	P(17)	2955.02693	4	P(24)	2546.70559	-21
R(15)	4188.90695	7	R(21)	4209.03841	-71	P(18)	2898.03796	-29	P(25)	2487.04762	30
R(16)	4197.49942	-10	R(22)	4204.99067	131	P(19)	2840.51520	-130	P(26)	2427.19891	-7
R(17)	4204.01435	-31	P(14)	3122.26159	158	P(20)	2782.51324	-64			
3-2											
R(0)	3658.60418	3	R(13)	3981.37559	13	P(5)	3417.99648	17	P(15)	2925.38191	9
R(1)	3693.68123	-77	R(14)	3993.19492	-78	P(6)	3373.33549	13	P(16)	2871.47977	-89
R(2)	3727.20008	143	R(15)	4003.01911	56	P(7)	3327.50933	-6	P(17)	2816.94772	-66
R(4)	3789.37342	59	R(16)	4010.82500	66	P(8)	3280.57165	17	P(18)	2761.83623	-34
R(5)	3817.94683	34	R(17)	4016.59619	73	P(9)	3232.57485	-25	P(19)	2706.19585	-23
R(6)	3844.78930	-208	R(18)	4020.31703	75	P(10)	3183.57399	0	P(20)	2650.07663	-20
R(8)	3893.14641	37	P(1)	3583.94832	-59	P(11)	3133.62210	7	P(21)	2593.52794	17
R(9)	3914.58613	6	P(2)	3544.46655	-17	P(12)	3082.77325	12	P(22)	2536.59693	17
R(11)	3951.83185	8	P(3)	3503.61335	-20	P(13)	3031.08114	3	P(23)	2479.33060	17
R(12)	3967.57974	19	P(4)	3461.44017	49	P(14)	2978.59941	-17	P(24)	2421.77333	-81
4-3											
R(0)	3493.99560	20	R(11)	3773.83739	-1	P(6)	3219.41883	77	P(15)	2786.85413	1
R(1)	3527.67136	23	R(12)	3788.60019	-17	P(7)	3175.22827	-11	P(16)	2734.72601	3
R(2)	3559.81985	-63	R(14)	3812.36316	46	P(8)	3129.94949	11	P(17)	2681.97169	6
R(3)	3590.40062	48	R(16)	3828.28684	-62	P(9)	3083.63280	-3	P(18)	2628.64051	14
R(5)	3646.68385	-55	P(1)	3422.24209	-247	P(10)	3036.33059	-11	P(19)	2574.78062	-5
R(6)	3672.30985	2	P(2)	3384.26078	-153	P(11)	2988.09512	8	P(20)	2520.43978	-20
R(7)	3696.20931	192	P(3)	3344.93901	-20	P(12)	2938.97789	4	P(21)	2465.66443	-26
R(8)	3718.34136	-31	P(4)	3304.32400	-19	P(13)	2889.03104	6	P(22)	2410.50038	44
R(10)	3757.18805	46	P(5)	3262.46678	-22	P(14)	2838.30615	14			
5-4											
R(2)	3396.14489	-130	P(2)	3227.62045	37	P(8)	2982.58526	-2	P(13)	2749.87993	259
R(3)	3425.40935	-18	P(3)	3189.78430	-194	P(9)	2937.88447	29	P(14)	2700.82405	-31
R(4)	3453.09161	-166	P(4)	3150.68542	16	P(10)	2892.21285	11	P(15)	2651.04911	-25
R(5)	3479.15768	5	P(5)	3110.36629	81	P(11)	2845.62142	29	P(16)	2600.60105	45
R(7)	3526.27593	-54	P(6)	3068.87592	5	P(12)	2798.15934	-6	P(17)	2549.52543	-15

<sup>a</sup> National Solar Observatory measurements.

TABLE 3  
LINE POSITIONS (IN  $\text{cm}^{-1}$ ) OF THE PURE ROTATIONAL LINES OF DF

J''	OBS	O-C	J''	OBS	O-C	J''	OBS	O-C	J''	OBS	O-C
v=0											
0	21.7183380	-1 a	14	317.98717	44 b	26	542.16514	-17 b	37	706.79187	-36 c
1	43.42268	10 b	15	338.05451	85 b	27	558.93647	-19 b	38	719.44246	-61 c
2	65.09863	-2 b	16	357.90753	119 b	28	575.36984	4 b	39	731.68274	-35 c
3	86.73251	-0 b	18	396.92146	-14 b	29	591.45645	1 b	40	743.50766	-2 c
4	108.31021	5 b	19	416.06039	-76 b	30	607.18887	24 b	41	754.91261	3 c
5	129.81770	2 b	20	434.93993	-50 b	31	622.55881	6 b	42	765.89402	19 c
6	151.24126	3 b	21	453.54830	-30 b	32	637.55972	20 b	43	776.44829	49 c
7	172.56709	2 b	22	471.87491	-24 b	33	652.18408	7 c	44	786.57138	22 c
8	193.78167	8 b	23	489.90965	-20 b	34	666.42552	-9 c	45	796.26003	-87 c
12	277.26032	138 b	24	507.64260	-19 b	35	680.27762	-46 c	46	805.51427	-5 c
13	297.71830	60 b	25	525.06428	-9 b	36	693.73522	-26 c	47	814.32935	35 c
v=1											
10	229.36362	-31 b	19	404.56290	-10 b	27	543.29197	68 b	35	660.88964	6 c
11	249.58956	25 b	20	422.90385	-57 b	28	559.23278	-28 b	36	673.91019	-13 c
12	269.65344	-10 b	21	440.98016	23 b	29	574.83511	29 b	37	686.53704	-48 c
13	289.54420	14 b	22	458.77923	3 b	30	590.08899	25 c	38	698.76560	-37 c
14	309.24930	79 b	23	476.29204	-15 b	31	604.98774	41 c	39	710.59057	-17 c
15	328.75519	44 b	24	493.50783	-134 b	32	619.52346	7 c	41	733.01159	48 c
16	348.05158	71 b	25	510.41955	-116 b	33	633.69000	-8 c	42	743.59754	-86 c
17	367.12637	117 b	26	527.01780	12 b	34	647.48108	20 c	43	753.76597	58 c
v=2											
11	242.68774	-19 b	17	356.91081	-42 b	29	558.50832	-2 c	34	628.85956	-108 c
12	262.19099	-7 b	25	496.04432	205 c	30	573.29046	-26 c	35	641.82869	-110 c
13	281.52421	43 b	26	512.14415	98 c	31	587.72335	-77 c	36	654.41807	83 c
14	300.67460	63 b	27	527.92766	99 c	32	601.80018	-123 c	37	666.61712	-20 c
15	319.63003	33 b	28	543.38427	-14 c	33	615.51490	-86 c	38	678.42581	124 c
16	338.37971	44 b									
v=3											
27	512.82225	-4 c	29	542.45396	23 c	31	570.74235	-35 c	32	584.36585	33 c
28	527.80356	154 c	30	556.76868	-107 c						

<sup>a</sup> Submillimeter-wave measurement of DeLucia et al. 1971.

<sup>b</sup> University of Waterloo measurements.

<sup>c</sup> National Solar Observatory measurements.

TABLE 4  
LINE POSITIONS (IN  $\text{cm}^{-1}$ ) IN THE VIBRATION-ROTATION BANDS OF DF

LINE	OBS	O-C	LINE	OBS	O-C	LINE	OBS	O-C	LINE	OBS	O-C
1-0											
R(0)	2927.78725	-4 a	R(14)	3154.18060	10 b	R(29)	3231.98674	-103 c	P(13)	2583.45204	-5 b
R(1)	2948.30660	-4 a	R(15)	3164.94859	7 b	R(31)	3228.42054	178 c	P(14)	2555.38789	-4 b
R(2)	2968.20599	-5 a	R(16)	3174.94579	6 b	P(1)	2884.94325	5 a	P(15)	2526.94524	-2 b
R(3)	2987.47230	3 a	R(17)	3184.16451	-8 b	P(2)	2862.64640	3 a	P(16)	2498.14010	-1 b
R(4)	3006.09249	6 a	R(18)	3192.59843	42 b	P(3)	2839.78537	-3 a	P(17)	2468.98849	-3 b
R(5)	3024.05393	-3 a	R(19)	3200.23886	-55 b	P(4)	2816.37489	2 a	P(18)	2439.50654	2 b
R(6)	3041.34460	-3 a	R(20)	3207.08299	31 b	P(5)	2792.42963	3 a	P(19)	2409.71011	-1 b
R(7)	3057.95269	9 a	R(21)	3213.12290	72 b	P(6)	2767.96456	-3 a	P(20)	2379.61531	5 b
R(8)	3073.86638	-1 a	R(22)	3218.35365	87 b	P(7)	2742.99505	1 a	P(21)	2349.23806	23 b
R(9)	3089.07498	3 a	R(23)	3222.76947	-35 c	P(8)	2717.53624	-8 a	P(22)	2318.59414	49 b
R(10)	3103.56756	-3 a	R(24)	3226.36891	-24 c	P(9)	2691.60400	7 a	P(23)	2287.69949	106 b
R(11)	3117.33405	-2 a	R(25)	3229.14685	-22 c	P(10)	2665.21349	-3 a	P(24)	2256.56754	-24 b
R(12)	3130.36458	1 a	R(26)	3231.10055	17 c	P(11)	2638.38085	2 a	P(25)	2225.21791	72 b
R(13)	3142.64958	-11 b	R(27)	3232.22458	-178 c	P(12)	2611.12169	-3 a			
2-1											
R(0)	2835.69993	-111 b	R(12)	3032.26417	-20 b	R(24)	3124.22514	57 c	P(7)	2655.85791	-15 b
R(1)	2855.65012	-37 b	R(13)	3044.13446	-16 b	R(25)	3126.75560	-207 c	P(8)	2631.06221	-21 b
R(2)	2874.99153	-21 b	R(14)	3055.26461	8 b	R(26)	3128.48179	166 c	P(9)	2605.80199	1 b
R(3)	2893.71165	-16 b	R(15)	3065.64579	7 b	R(27)	3129.38973	62 c	P(10)	2580.09193	-10 b
R(4)	2911.79761	-43 b	R(16)	3075.26948	-76 c	R(28)	3129.48388	165 c	P(11)	2553.94798	-2 b
R(5)	2929.23772	-37 b	R(17)	3084.12987	-73 c	R(29)	3128.75719	-32 c	P(12)	2527.38536	-3 b
R(6)	2946.01971	-26 b	R(18)	3092.21897	-80 c	P(1)	2794.03091	0 b	P(13)	2500.41979	2 b
R(7)	2962.13194	-11 b	R(19)	3099.52994	-124 c	P(2)	2772.33720	-41 b	P(14)	2473.06664	-14 b
R(8)	2977.56311	7 b	R(20)	3106.05807	-64 c	P(3)	2750.09018	-65 b	P(15)	2445.34320	114 b
R(9)	2992.30196	-11 b	R(21)	3111.79627	-48 c	P(4)	2727.30446	-41 b	P(16)	2417.26117	-10 b
R(10)	3006.33853	-10 b	R(22)	3116.73981	-31 c	P(5)	2703.99395	-30 b	P(19)	2331.03972	61 b
R(11)	3019.66241	-21 b	R(23)	3120.88430	16 c	P(6)	2680.17336	-32 b	P(21)	2272.06406	30 b
3-2											
R(0)	2745.50964	39 c	R(9)	2897.49155	-12 c	R(19)	3000.78863	35 c	P(6)	2594.19124	18 b
R(1)	2764.89905	15 c	R(10)	2911.07610	-8 c	R(20)	3006.99533	-19 c	P(7)	2570.51439	-44 b
R(2)	2783.69155	4 c	R(11)	2923.96068	-26 c	R(22)	3017.07655	43 c	P(8)	2546.36707	-12 c
R(3)	2801.87440	8 c	R(12)	2936.13615	-23 c	R(23)	3020.93938	-8 c	P(9)	2521.76281	-20 c
R(4)	2819.43496	6 c	R(13)	2947.59304	-32 c	P(1)	2704.99136	15 c	P(10)	2496.71661	-67 c
R(5)	2836.36109	-3 c	R(14)	2958.32288	-26 c	P(2)	2683.88959	-8 c	P(11)	2471.24434	-73 c
R(6)	2852.64122	4 c	R(15)	2968.31793	52 c	P(3)	2662.24460	-17 c	P(13)	2419.08144	-51 c
R(7)	2868.26355	-8 c	R(17)	2986.06815	-17 c	P(4)	2640.07035	-17 c	P(14)	2392.42100	-54 c
R(8)	2883.21728	-9 c	R(18)	2993.81081	30 c	P(5)	2617.38038	-77 b			
4-3											
R(0)	2657.08308	3 c	R(8)	2790.69188	-5 c	R(16)	2881.69100	11 c	P(4)	2554.54475	-48 c
R(1)	2675.92015	-206 c	R(9)	2804.50482	-19 c	R(17)	2889.82721	26 c	P(5)	2532.46382	-6 c
R(2)	2694.17510	32 c	R(10)	2817.64019	0 c	R(18)	2897.21710	-39 c	P(6)	2509.89038	-5 c
R(3)	2711.82851	25 c	R(11)	2830.08733	-29 c	R(19)	2903.85537	-59 c	P(7)	2486.83912	-4 c
R(4)	2728.87050	10 c	R(12)	2841.83769	-12 c	R(20)	2909.73711	88 c	P(8)	2463.32447	-2 c
R(5)	2745.28951	23 c	R(13)	2852.88236	65 c	R(21)	2914.85236	-28 c	P(9)	2439.35953	-145 c
R(6)	2761.07347	17 c	R(14)	2863.21052	-11 c	P(2)	2597.17542	6 c	P(10)	2414.96323	-4 c
R(7)	2776.21117	1 c	R(15)	2872.81625	-6 c	P(3)	2576.12051	14 c	P(11)	2390.14589	-22 c
5-4											
R(6)	2671.17047	20 c	R(11)	2737.88914	-25 c	R(15)	2778.98156	-19 c	P(4)	2470.59161	-13 c
R(7)	2685.82734	0 c	R(12)	2749.21279	-84 c	R(16)	2787.47534	-29 c	P(5)	2449.10492	-67 c
R(8)	2699.83880	71 c	R(13)	2759.84325	48 c	R(17)	2795.24272	15 c	P(6)	2427.13490	-39 c
R(9)	2713.19220	16 c	R(14)	2769.76873	52 c	P(3)	2491.58076	87 c	P(7)	2404.69448	-33 c

<sup>a</sup> NRC measurements.

<sup>b</sup> University of Waterloo measurements.

<sup>c</sup> National Solar Observatory measurements.

TABLE 5  
ROTATIONAL CONSTANTS FOR HF (IN  $\text{cm}^{-1}$ )

Constants	$v = 0$	$v = 1$	$v = 2$	$v = 3$	$v = 4$	$v = 5$
$T_v$ .....	0.0	3961.422490 (19)	7750.793323 (75)	11372.80411 (17)	14831.64203 (24)	18130.93866 (39)
$B_v$ .....	20.55973066 (42)	19.7874717 (13)	19.0349598 (25)	18.3006000 (51)	17.5825644 (81)	16.878753 (21)
$10^3 \times D_v$ .....	2.119960 (15)	2.0637007 (102)	2.010084 (20)	1.959512 (42)	1.912272 (70)	1.86896 (34)
$10^7 \times H_v$ .....	1.63793 (64)	1.58711 (29)	1.53556 (57)	1.4821 (13)	1.4172 (22)	1.344 (19)
$10^{11} \times L_v$ .....	-1.5528 (111)	-1.4840 (32)	-1.4754 (66)	-1.508 (16)	-1.442 (21)	-1.50 (35)
$10^{15} \times M_v$ .....	1.480 (85)	0.950 (12)	0.834 (26)	0.829 (74)	...	...
$10^{19} \times N_v$ .....	-1.23 (24)	...	...	...	...	...

TABLE 6  
ROTATIONAL CONSTANTS FOR DF (IN  $\text{cm}^{-1}$ )

Constants	$v = 0$	$v = 1$	$v = 2$	$v = 3$	$v = 4$	$v = 5$
$T_v$ .....	0.0	2906.661542 (15)	5721.818201 (94)	8447.35379 (15)	11085.02390 (23)	13636.44457 (34)
$B_v$ .....	10.86034387 (20)	10.56402755 (48)	10.2733195 (15)	9.9879411 (31)	9.7075572 (75)	9.4318026 (97)
$10^4 \times D_v$ .....	5.874588 (31)	5.760898 (41)	5.650154 (63)	5.54395 (17)	5.44187 (68)	5.34397 (69)
$10^8 \times H_v$ .....	2.38133 (54)	2.33271 (78)	2.26777 (79)	2.2147 (30)	2.147 (22)	2.038 (13)
$10^{12} \times L_v$ .....	-1.1428 (34)	-1.1386 (55)	-1.0094 (29)	-1.018 (15)	-0.88 (22)	...
$10^{17} \times M_v$ .....	4.187 (69)	4.03 (13)	...	...	...	...

sorption measurements from Ottawa. The new HF pure rotation line positions are reported in Table 1 and the vibration-rotation line positions in Table 2. The DF lines are reported in Tables 3 and 4.

The observed spectral line positions of HF and DF bands were fit using the usual  $^1\Sigma^+$  energy level expression:

$$F_v(J) = T_v + B_v J(J+1) - D_v [J(J+1)]^2 + H_v [J(J+1)]^3 + L_v [J(J+1)]^4 + M_v [J(J+1)]^5 + N_v [J(J+1)]^6. \quad (1)$$

In the final least-squares fit approximate weights for the individual rotational lines were chosen on the basis of the expected experimental precision. For the HF molecule all of the previous line positions used in the fit by LeBlanc et al. (1994) were included. For DF a single  $J = 1-0$  pure rotation transition (DeLucia et al. 1971) was added to the data set.

The HF and DF data cover the first six vibrational levels,  $v = 0-5$ . The rotational constants for HF are reported in Table 5 and the constants for DF in Table 6. Notice that the high-order constant  $M_v$  was required for  $v = 0-3$  for HF and  $N_v$  was also determined for  $v = 0$ . Our energy levels for HF  $v = 3$  are  $0.0048 \text{ cm}^{-1}$  higher than the recent laser measurements of Sasada (1994).

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