

# MICROWAVE AND RADIO-FREQUENCY RESONANCE LINES OF INTEREST TO RADIO ASTRONOMY

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A review of microwave and radio-frequency spectral lines which might possibly be detected by the techniques of radio astronomy is attempted here. Brief discussions of this type have already been given by several authors [1, 2, 3, 4]. However, the present treatment is somewhat more complete than previously published material, and has the advantage of more recent information about certain transition frequencies. It includes a general discussion of types of spectra which might be found, expected intensities, and some characteristics and known frequencies of the lines which may be of interest in radio astronomy.

Transitions which lie in the microwave or radio-frequency region can be expected to come from atomic or molecular hyperfine structure, from atomic or molecular fine structure, and from molecular rotational frequencies. It is of course possible that some odd circumstance or chance makes two electronic levels which are not fine structure of the same level fall so close together that a transition between them corresponds to a microwave frequency. However, there seem to be no known 'accidents' of this type that are of interest to radio astronomy. It is also possible that some molecular vibration be hindered by just the precise amount required to reduce its frequency to the microwave or radio-frequency region. This occurs in the well-known case of ammonia, but there seems to be no possibility of another case that would be of importance to radio astronomy. The only other varieties of sharply resonant microwave or radio-frequency transitions which have so far been found in the laboratory are transitions between Zeeman or Stark components of one or neighbouring energy levels. However, such transitions fall in the interesting frequency regions only when the magnetic or electric fields are rather large, and to be sharp and easily detectable they require a homogeneity of the field that is not

likely to occur over any resolvable region of an astronomical object. Hence we shall be concerned only with hyperfine structure, fine structure, molecular rotational frequencies and the inversion spectrum of ammonia.

### I. INTENSITIES OF LINES

The intensity of a microwave or radio-frequency transition may be represented to a reasonable approximation by an absorption coefficient given by [5]\*

$$\gamma = \frac{8\pi^2 n |\mu|^2}{3ckT} \frac{\nu^2 \Delta\nu}{(\nu - \nu_0)^2 + (\Delta\nu)^2}, \quad (1)$$

where  $\gamma$  is the absorption coefficient per unit length,

$n$  is the density of atoms or molecules in the lower of the two levels between which the transition occurs,

$|\mu|^2$  is the square of the dipole moment matrix element (averaged over the magnetic quantum number  $M$ ),

$c$ ,  $k$ ,  $T$  are, as usual, the velocity of light, Boltzmann's constant, and the absolute temperature respectively,

$\nu$  is the frequency being considered or measured,

$\nu_0$  is the resonant or central frequency of the transition,

$\Delta\nu$  is the half-width of the resonance at half-intensity.

Expression (1) applies strictly only when  $h\nu \ll kT$  and when a Lorentz-type line shape occurs. However, it is sufficiently accurate for our purpose in any case which will be encountered below.

At the peak intensity where  $\nu = \nu_0$ , (1) becomes

$$\gamma = \frac{8\pi^2 n |\mu|^2 \nu^2}{3ckT\Delta\nu}. \quad (2)$$

If the line width is primarily due to collisions with other atoms or molecules,  $\Delta\nu$  is proportional to the total pressure and is of the order 10 Mc./s. at a pressure of 1 mm. Hg, or when the total density  $N$  of molecules is approximately  $3.5 \times 10^{16}$ . Hence, inserting values, (2) becomes

$$\gamma = \frac{2 \times 10^{-19} n \nu'^2 |\mu'|^2}{NT}, \quad (3)$$

where  $\gamma$  is in  $\text{cm.}^{-1}$ ,

$\nu'$  is in Mc./s.

$\mu'$  is in Debye units ( $10^{-18}$  e.s.u.) or  $10^{-18}$  e.m.u.

\* Background for, and details connected with, much of the following material can be found in reference [5].

Except for the atmospheres of planets or stars, the line broadening in astronomical objects usually comes primarily from Doppler effects rather than from collisions (or pressure broadening). In this case,  $\Delta\nu$  depends on the distribution of velocities in the medium being observed. Assuming that velocities of the gases observed vary more or less randomly by about

$\pm 10$  km./sec.,  $\Delta\nu$  may be taken as  $\frac{\nu}{3 \times 10^4}$ , so that (2) becomes

$$\gamma \approx \frac{6 \times 10^{-15} n |\mu'|^2}{T\lambda} \approx \frac{5 \times 10^{-19} n |\mu''|^2}{T\lambda}, \quad (4)$$

where  $\gamma$  is in  $\text{cm.}^{-1}$  if  $\lambda$  is in  $\text{cm.}$ ,

$n$  is the number of atoms or molecules in the lower state of the transition per c.c.,

$\mu'$  is the dipole matrix element in Debye ( $10^{-18}$  e.s.u.) or  $10^{-18}$  e.m.u.,

$\mu''$  is the dipole matrix element in Bohr magnetons ( $0.922 \times 10^{-20}$  e.m.u.).

Consider now the case where a radio telescope is directed towards a uniform gas which completely fills the field of view and behind which there is a uniform background of radiation with some effective temperature  $T_B$  as judged by the amount of radio-frequency radiation at the frequency of interest. If the effective temperature of the gas (determined by the relative population of the upper and lower states of the transition considered) is  $T$ , the change in apparent temperature due to the gas resonance is

$$\Delta T = (T - T_B) (1 - e^{-\gamma L}), \quad (5)$$

where  $L$  is the length of the column of gas. For detection of this change,  $\Delta T$  must be about as large as  $1^\circ$ , in which case we may expect that  $\gamma L \ll 1$ , and (6) can be written

$$\Delta T \approx (T - T_B) \gamma L. \quad (6)$$

Frequently  $T_B \ll T$ , and (6) combined with (4) gives

$$\Delta T \approx \frac{6 \times 10^{-15} n |\mu'|^2 L}{\lambda} \approx \frac{5 \times 10^{-19} n |\mu''|^2 L}{\lambda}. \quad (7)$$

Thus for detection, the column of gas must contain about  $2 \times 10^{14} \lambda$  molecules of the right type per  $\text{cm.}^2$  if the matrix element is due to an electric dipole ( $|\mu'| \approx 1$ ), or  $2 \times 10^{18} \lambda$  if it is due to a magnetic dipole ( $|\mu''| \approx 1$ ).

It is of course the number of atoms or molecules having a resonance at the desired frequency that must be considered. Molecules of a given species may in some cases be distributed among a wide variety of levels, so that only a small fraction of them effectively respond to a given radio frequency. However, at low temperatures, molecules or atoms will in many of the cases considered below be concentrated in only a very few levels, so that the total number of a given species is not much greater than the number in a particular state involved in the radio-frequency transition.

If one considers interstellar gas in our own or a similar Galaxy, then the largest dimension is about  $L \approx 10^{23}$  cm., and the average molecular density must be as large as  $n > 2 \times 10^{-9} \lambda$  or

$$n > 2 \times 10^{-5} \lambda \quad (8)$$

respectively for electric or magnetic dipole moments.

As has been suggested [6], it may be possible to use sufficiently large antennas so that some of the bright continuous sources give effective background temperatures  $T_B$  several powers of 10 greater than the gas temperature, and thus considerably reduce the molecular (or atomic) density indicated by (8) as necessary for detection.

Normally, transitions between different levels of fine or hyperfine structure involve no electric dipole moment matrix element, but rather a magnetic dipole matrix element of the order of one Bohr magneton ( $|\mu''| \approx 1$ ) or in some cases only a nuclear magneton ( $|\mu''| \approx 10^{-3}$ ). Molecular rotational transitions, on the other hand, normally involve electric dipole matrix elements, and are of the order of 1 Debye ( $|\mu'| \approx 1$ ). Hence fine or hyperfine structure transitions are often much weaker than those between rotational levels, and require a much larger density  $n$  for detection. There are, however, some important exceptions to this generalization, which occur when so-called fine structure is not due to the effects of magnetic moments, or when the fine or hyperfine structure is comparable in magnitude to the separations between levels unsplit by the effects of electron spin or nuclear moments. These include the following cases where there is an electric dipole matrix element between fine or hyperfine structure levels:

(1) Transitions between  $ns$  and  $np$  levels of hydrogen-like atoms. In principle, other very close coincidences between two electronic levels might occur in more complex atoms, but no other cases are known that are of concern here.

(2) Transitions between  $\Lambda$ -doublets, as in the OH microwave spectrum.

(3) Transitions between hyperfine levels of a symmetric top molecule

that involve  $K$ -degeneracy. No cases of this type are likely to be of importance to radio astronomy.

(4) The so-called 'fine' structure of ammonia, the inversion spectrum.

Tables 1, 2, 3 and 4 give information about most of the microwave and radio-frequency transitions which are at present known and which may have sufficient intensities to warrant consideration for the purposes of radio astronomy.\*

No transitions are listed with frequencies greater than 300,000 Mc./s. ( $\lambda = 1$  mm.), since sensitive radio-detection can probably not soon be achieved at these high frequencies. In many cases lines are listed for completeness or comparison which are probably too weak for detection in any astronomical object. Since all microwave and radio-frequency lines are rather weak, it seems improbable that any will be found in astronomical objects before their frequencies are fairly accurately known from laboratory or very precise theoretical work. Because of this great importance of precise frequencies, there is a rather generous listing of transitions whose frequencies are now known, even though in some cases it seems unlikely that they are sufficiently intense for detection by radio telescopes.

## 2. HYPERFINE TRANSITIONS

Atomic hyperfine structure occurs only for nuclei with spin greater than zero (except for isotope shifts, which are sometimes called hyperfine structure, but are of no interest here). Such nuclei are relatively rare, the commonest being  $H^1$ ,  $H^2$  and  $N^{14}$ . Atoms of the latter two are less abundant than those of  $H^1$  by a factor of several thousand, according to the usual estimates [7]. All other nuclei with non-zero spin are less abundant even than  $H^2$  and  $N^{14}$  by a factor of about 100, and hence in most cases their hyperfine transitions can probably not be detected by radio astronomical techniques, except under some very special circumstances. Table 1 lists characteristics of these hyperfine lines, including all atomic hyperfine transitions with known frequencies from atoms of abundance not less than about  $10^{-6}$  that of  $H^1$ .

In addition to  $H^1$  and  $H^2$ , the h.f.s. of various stages of ionization of  $N^{14}$  and of  $He^3$  II seem to be interesting cases for radio astronomy. Unfortunately, the frequency for  $N$  I only has so far been measured experimentally, and this frequency is so low that its detection seems quite difficult. The h.f.s. frequencies for  $N$  VII and  $He^3$  II can be calculated with some

\* Most of the information in these tables and references to original sources may be found in references [5] and [8].

Table 1. *Some hyperfine structure transitions of interest to radio astronomy*

The approximate abundances of each nuclear species relative to  $H^1$  for our Galaxy are given. These are not necessarily the relative abundance in interstellar gases, where  $H^1$  has a density of 1 atom./cm.<sup>3</sup>. The matrix element for each transition is due to a magnetic dipole, and is approximately one Bohr magneton ( $|\mu''| = 1$ ). The quantity  $F$  is the vector sum of electronic angular momentum  $J$  and nuclear spin  $I$ .

Nucleus	Abundance relative to $H^1$	Transition	Frequency (Mc./s.)	Comments
$H^1$	1	$H\ I\ 2S_{1/2},\ F=0-1$	1420.4051	Already detected in interstellar gases
$H^2$	$2 \times 10^{-4}$	$H\ I\ 2S_{1/2},\ F=1/2-3/2$	327.3842	
$He^3$	$10^{-5}$	$He\ II\ 2S_{1/2},\ F=1-0$	8659.3*	Calculated frequency without allowance for finite nuclear size
$He^3$	$10^{-5}$	$He\ I\ 3S_{3/2} - 3S_{1/2}$	6739.71	Metastable state
$N^{14}$	$5 \times 10^{-4}$	$N\ I\ 2^3p^4S_{3/2},\ F=3/2-5/2$	26.12	
		$N\ I\ 2^3p^4S_{3/2},\ F=1/2-3/2$	15.67	
		$N\ II\ 2p^2^3P_1,\ F=1-2$	$\sim 500$	Approx. 60 cm. <sup>-1</sup> above ground state
		$N\ II\ 2p^2^3P_1,\ F=0-1$		
		$N\ III\ 2p^2P_{1/2},\ F=1/2-3/2$	$\sim 800$	
		$N\ V\ 2s^2S_{1/2},\ F=1/2-3/2$	$\sim 3000$	
		$N\ VII\ 1S^2S_{1/2},\ F=1/2-3/2$	53.060	Calculated frequency without allowance for finite nuclear size
$Na^{23}$	$1 \times 10^{-6}$	$Na\ I\ 3s^2^2S_{1/2},\ F=1-2$	1771.61	
$Al^{27}$	$3 \times 10^6$	$Al\ I\ 3p^2P_{1/2},\ F=2-3$	1450	
$P^{31}$	$4 \times 10^{-7}$	$P\ I\ 3^3p^4S_{3/2},\ F=2-3$	112	
$Cl^{35}$	$4 \times 10^{-7}$	$Cl\ I\ 3p^5^2P_{3/2},\ F=3-2$	670.018	
		$F=2-1$	355.244	
		$F=1-0$	150.145	

\* *Note added in proof:* Novick (private communication) has now calculated this transition frequency for the  $He^3\ II$  ground state as  $8665.66 \pm 0.18$  Mc./s. from recent measurements on the  $He^3\ II\ 2s$  state [R. Novick and E. Commins, *Phys. Rev.* **103**, 1897, 1956]. The calculation includes small electrodynamic corrections evaluated by Mittelman (to be published).

accuracy, and their precise experimental determination would be of considerable interest to physics as well as to astronomy because of a slight modification of the frequencies due to the finite nuclear size (hyperfine structure anomaly). Frequency changes of this type are, however, not very large, and particularly in the case of  $He^3$  the resulting uncertainty should not be large enough appreciably to complicate a search for this line. Assuming abundances similar to those on earth,  $He^3$  is considerably less abundant than  $H^2$ . However, the fact that its resonant wave-length is so much shorter than that for  $H^2$  makes it approximately as favourable (cf. equation (8)), assuming that a large fraction of He atoms are ionized.

### 3. FINE STRUCTURE

It is only the lightest atoms for which the fine structure in the ground or lower states is sufficiently small to give transitions in the microwave region. In fact, the most interesting cases are limited to H, D, He II and perhaps N I which are listed in Table 2. Although small fine-structure spacings do occur in excited states of heavier atoms, these states are so short-lived that their microwave spectra would not be detectable in astronomical objects. The  $n = 2$  state of hydrogen-like atoms has some characteristics which may make it detectable by radio telescopes, even though the abundance of this excited state may be very small. In particular, the transitions between  $2s$  and  $2p$  states involve a rather large electric dipole moment ( $|\mu'| = 6.2$  for H). Furthermore, the frequency is accurately known and the  $2s$  level is metastable (with a lifetime of 8 sec. in the case of hydrogen). Hence an appreciable number of atoms may accumulate in it.

Table 2. *Atomic fine structure transitions of interest to radio astronomy*

The relative abundances given are those for atoms in the ground states. All cases listed are metastable excited states.

Atom	Abundance relative to H	Transition	Frequency (Mc./s.)
H	1	H I $^2S_{1/2} - ^2P_{1,2}$	1057.8
		H I $^2P_{3/2} - ^2S_{1/2}$	9912.6
He	$10^{-1}$	He II $^2S_{1/2} - ^2P_{1/2}$	14.020
		$^2P_{3/2} - ^2S_{1/2}$	161.510
N	$5 \times 10^{-4}$	N I $2p^3 \ ^3D_{5/2} - ^3D_{3/2}$	240.000

Since the  $2p$  levels are not metastable, they will contain much fewer atoms than do the  $2s$  levels. Hence these transitions will be strengthened by approximately the factor  $\frac{kT}{k\nu_0}$ , where  $\nu_0$  is the transition frequency.

However, the instability of the  $2p$  levels greatly widens the resonance transition so that  $\Delta\nu \sim 50$  Mc./s. (for H). This decreases the peak intensity by a factor of about 1000 over the cases where Doppler broadening predominates. This factor of 1000 is not all loss, since the receiver band-width should be increased to about 100 Mc./s. for detection of this line, and the minimum detectable temperature change should thus be decreased to perhaps  $0.1^\circ$  C. The net result is that for the  $^2S_{1/2} - ^2P_{3/2}$  or the  $^2S_{1/2} - ^2P_{1/2}$  transition, the minimum detectable density of atoms in interstellar space is of the order of  $10^{-11}/\text{cm.}^3$ , or the total number required in the line of sight is about  $10^{12}/\text{cm.}^2$  assuming  $T_B < T$  (cf. equation 6). An accurate estimate of the density of H atoms in the  $2s$  state is difficult. However, the

numbers required do not seem impossibly large. A more detailed discussion has been given by J. P. Wild [10]. J. E. Blamont (private communication) has considered radiation of this type from planetary nebulae.

#### 4. MOLECULAR ROTATIONAL SPECTRA

In addition to fine and hyperfine structure, molecules have rotational levels which are often sufficiently close to produce microwave transitions. Microwave rotational transitions which may be of interest to radio astronomy are listed in Table 3.

Table 3

Some microwave transitions between molecular rotational levels of interest to radio astronomy. The inversion spectrum of  $\text{NH}_3$  is also listed.

Molecule	Electronic state	Transition	Frequency (Mc./s.)	Matrix element in Debye units	Comments
CaH	$^2\Sigma$	$J=3/2-1/2$	254,080	Electric dipole unknown	
		$J=1/2-1/2$	252,650		
CO	$^1\Sigma$	$J=1-0$	115,270.6	0.10	
CO <sup>+</sup>	$^2\Sigma$	$J=3/2-1/2$ $1/2-1/2$	117,980	Electric dipole unknown	
CS	$^1\Sigma$	$J=1-0$	48,991.0	2.0	
NO	$^2\Pi_{1/2}$	$J=3/1-1/2$	150,176.3	0.07	Also other nearby lines due to h.f.s.
H <sub>2</sub> O	$^1\Sigma$	$6_{1,6} - 5_{2,3}$	22,235.22	0.16	
N <sub>2</sub> O	$^1\Sigma$	$J=1-0$	25,123.28	0.17	Other lines at multiples of the frequency given. Very small h.f.s. present
HCN	$^1\Sigma$	$J=1-0, F=1-1$	88,600.1	1.72	Also <i>l</i> -doublet transitions may occur
		$F=2-1$	88,601.5	2.22	
		$F=0-1$	88,603.6	0.99	
CH <sub>3</sub>					Structure and spectrum unknown, but may produce some microwave lines
NH <sub>3</sub>					Structure and spectrum not well known, but probably produces some microwave lines
NH <sub>3</sub>	$^1\Sigma$	Inversion, $J=1, K=1$	23,694.48	1.0	Also other inversion transitions at nearby frequencies
O <sub>3</sub>	$^1\Sigma$	$1_{11}-2_{02}$	42,832.62	0.17	Also other rotational transitions
		$1_{11}-0_{00}$	118,364.3	0.53	

Probably only the diatomic molecules of Table 3 exist in detectable abundance in interstellar space; CaH and CN seem to be the only ones



yet found there by optical spectroscopy. Of the common hydrides, CaH has the lowest rotational frequency which, even so, is near the border of the range of present microwave techniques. The other molecules listed may possibly be found in planetary atmospheres, in comets, or in some other regions of gaseous concentrations. A suitable telescope with resolution near to one minute of arc, for example, could very probably detect  $\text{NH}_3$  lines in the atmosphere of Jupiter. Omission from the table of certain common molecules such as  $\text{N}_2$  and  $\text{CO}_2$  may strike the reader. They lack electric dipole moments and hence have no rotational spectra.

## 5. MOLECULAR HYPERFINE STRUCTURE

The only molecules of sufficient abundance and with sufficiently large hyperfine structure to be interesting to radio astronomy seem to be the hydrides which are in  $^2\Sigma$  or  $^3\Sigma$  states. Hydrides in electronic  $^2\Pi$  states have considerably smaller h.f.s. (cf. OH, Reference [5]). Of the  $^2\Sigma$  and  $^3\Sigma$  hydrides,  $\text{H}_2^+$ , NH,  $\text{OH}^+$  and CaH are probably the most abundant. They should all give hyperfine structure of the same order of magnitude as that found in the  $1S$  state of atomic hydrogen. Unfortunately, these hyperfine transitions involve only magnetic dipole matrix elements as in atomic H, and this coupled with the lower abundance of the molecules and uncertainty in the precise frequencies of transition will make their detection quite difficult.

The most interesting of the above hydrides appears to be  $\text{H}_2^{+*}$  because it may be more abundant than the others, and also because its hyperfine frequencies can be obtained with some accuracy from calculations, even though there seems to be little immediate hope of their measurement in the laboratory. The ground rotational state of  $\text{H}_2^+$  is ionized parahydrogen, and hence has no hyperfine structure. Orthohydrogen does have hyperfine structure and exists in the states  $J = 1/2$  and  $J = 3/2$  which are about  $60 \text{ cm.}^{-1}$  above the ground state. In regions of low temperature it will of course be considerably less abundant than parahydrogen.

In orthohydrogen, the electron spin-nuclear spin coupling constant is of the order of one or two thousand megacycles/sec., whereas the electron spin-rotational motion coupling should be about a factor of ten less. The electron and nuclear spins would then be coupled together fairly strongly, and their resultant added vectorially to the end-over-end rotation, giving coupling case ( $b_{\beta S}$ ) (cf. Reference [5], sec. 8-2).

\* The possible value of this molecule to radio astronomy was suggested some time ago by B. Burke.

One may expect the lowest rotational state of orthohydrogen with either  $J = 1/2$  or  $J = 3/2$  to have hyperfine structure transitions with frequencies somewhere near the value for the hyperfine transition already detected in atomic hydrogen. A much more exact theoretical estimate of the hyperfine frequencies in  $\text{H}_2^+$  can be made by some numerical work, since the electronic wave-functions can be obtained with precision [9]. However, a precise estimate will also involve evaluation of the fine-structure doubling (in this case much smaller than the hyperfine structure), which gives a deviation from pure coupling case ( $b_{\beta S}$ ).

## 6. MOLECULAR FINE STRUCTURE

Molecular fine structure occurs with widely varying characteristics. The most interesting type of molecular fine structure from the point of view of radio astronomy is  $\Lambda$ -type doubling, since transitions between  $\Lambda$  doublets can involve electric dipole moments and hence are enormously more intense than most of the other fine-structure transitions, which involve only magnetic dipole moments. The most abundant molecules with this type of spectra are CH, OH and SiH.\* Data on these and some other molecules are given in Table 4. Only in the case of OH are the  $\Lambda$ -doublet frequencies accurately known. This molecule appears, in fact, to be susceptible to detection by radio telescopes. Its average abundance in interstellar space needs to be about  $10^{-6}/\text{cm}^3$  for detection against a normal background, or considerably less for detection by absorption of radiation from a high-intensity source. Furthermore, the frequency of the strongest transition lies near the region where considerable apparatus has already been developed for study of the hydrogen lines.

Fine structure splittings between  $^2\Pi_{\frac{1}{2}}$  and  $^2\Pi_{\frac{3}{2}}$  levels correspond roughly to atomic fine structure, and are too large to fall in the microwave region for the lowest states of any molecule which would be abundant enough to be of interest here.

There are a variety of molecules in  $^2\Sigma$  or  $^3\Sigma$  states that involve spin ( $\rho$ -type) doubling or tripling with separations corresponding to microwave or radio frequencies. These transitions are weak because they have only magnetic dipole matrix elements. However, some, such as those of  $\text{O}_2$ , can certainly be observed by absorption in the earth's atmosphere, and perhaps might be found in comets or other planetary atmospheres if telescopes of sufficiently high resolution are available. The more favourable cases of these types of fine structure transitions are also listed in Table 4.

Table 4. *Some molecular fine-structure transitions of interest to radio astronomy*

Transitions between $\Lambda$ -doublets [electric dipole, $ \mu'  \sim 1$ ]				
Molecule	Electronic state	Transition	Frequency (Mc./s.)	Comments
CH	${}^2\Pi_{1/2}$	$J=1/2$	$\sim 1000$	Also transitions at higher frequencies $\sim 1000N(N+1)$ in excited rotational states
	${}^2\Pi_{3/2}$	$J=3/2$		
OH	${}^2\Pi_{3/2}$	$J=3/2, F=2-2$	1665.0	Also, weak hyperfine satellites and higher frequencies in excited rotational states
		$F=1-1$	1667.0	
AlH	${}^1\Pi$	$N=1$	380	Also higher frequencies in excited rotational states
SiH	${}^2\Pi_{1/2}$	$J=1/2$	2400	Also higher frequencies in excited rotational states
SH	${}^2\Pi_{3/2}$	$J=3/2$	114	Also higher frequencies in excited rotational states
Transitions between spin fine-structure levels [magnetic dipole, $ \mu''  \sim 1$ ]				
H <sub>2</sub> <sup>+</sup>	${}^2\Sigma$	$N=1$	$\sim 100$	Approx. 60 cm. <sup>-1</sup> above ground state
NH	${}^3\Sigma$	$N=1, J=0-1$	26,000	
		$J=1-2$	13,000	
OH <sup>+</sup>	${}^3\Sigma$	$N=1, J=0-1$	133,000	
		$J=1-2$	63,000	
MgH	${}^2\Sigma$	$N=1$	1000	
CaH	${}^2\Sigma$	$N=1$	1500	
CN	${}^3\Sigma$	$N=1$	360	
CO <sup>+</sup>	${}^3\Sigma$	$N=1$	450	
O <sub>2</sub>	${}^3\Sigma$	$N=1, J=0-1$	118,750.5	Also known frequencies for other rotational levels
		$J=1-2$	56,265.6	
		$N=3, J=2-3$	62,487.4	
		$J=3-4$	58,446.2	

## 7. GENERAL CONCLUSIONS

There is a limited number of radio frequency resonances for which immediate search with radio telescopes appears justified. Of these, the  $\Lambda$ -doubling of OH, the hyperfine structure of H<sup>2</sup> and perhaps of He<sup>3</sup> II are outstanding. A number of additional resonances can probably be found if their frequencies can be first accurately determined in the laboratory. These include the  $\Lambda$ -doubling of CH and the hyperfine structure of ionized N<sup>14</sup>.

The construction of radio telescopes with very high resolving power should considerably increase the possibility of finding line spectra of astronomical interest. Such telescopes should yield a considerable increase

\* References [1] and [2] list also CH<sup>+</sup> as producing  $\Lambda$ -doubling. This is apparently due to the incorrect assumption that the CH<sup>+</sup> molecule occurs in a  ${}^2\Pi$  state. Its ground state is  ${}^1\Sigma$ .

in background temperature when directed towards one of the intense continuous sources and hence increased sensitivity for detection of absorption lines. They should also allow examination of the regions of high concentrations of gaseous matter, such as occur in planetary atmospheres, in comets, or in small nebulae.

Additional absorption or emission lines due to gases in the earth's atmosphere are probably immediately detectable; the most obvious of these cases is the rich microwave spectrum of O<sub>2</sub>.

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