Chapter 3

Radio astronomy

	page
The major radio surveys	142
Microwave background	143
Selected discrete radio sources	145
The brightest radio sources visible in the northern hemisphere	148
Radio spectra	150
Radio flux calibrators	151
Radio propagation effects	153
The Earth's atmosphere	153
Interplanetary medium	153
Interstellar medium (*delay and Faraday rotation*)	154
Interstellar medium (*scintillation*)	155
Atmospheric opacity	155
Ionospheric electron density	156
Spectral features	157
Bibliography	157

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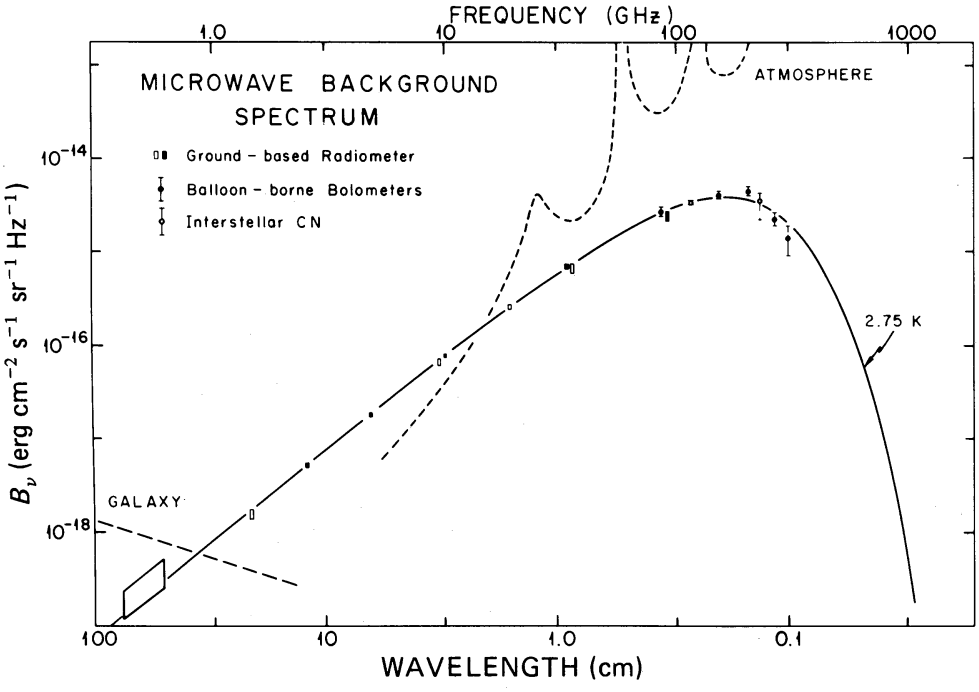
The major radio surveys

Observatory	Survey	ν (MHz)	Sources	Limit (Jy)[a]
Cambridge	3C	159	471	8
	3CR	178	—	9
	4C	178	4843	2
	5C	408	276	0.025
	WKB	38	1069	14
	RN	178	87	0.25
	NB	81.5	558	1
Mills Cross	MSH	86	2270	7
Parkes	PKS	408, 1410, 2650	297	4
	PKS	408, 1410	247	0.5
	PKS	408, 1410	564	0.3
	PKS	408, 1410	628	0.4
	PKS	635, 1410, 2650	397	1.5
Owens Valley	CTA	906	106	—
	CTB, CTBR	960	110	—
	CTD	1421	—	1.15
National Radio Observatory	NRAO	750, 1400	726	(3C and 3CR)
	NRAO	750, 1400	458	0.5
Bologna	B1	408	629	1
	B2	408	3235	0.2
Ohio State	O	1415	128	2, 0.5
	O	1415	236	0.37
	O	1415	1199	0.3
	O	1415	2101	0.2
Vermillion River	VRO	610.5	239	0.8
	VRO	610.5	625	0.8
Dominion Radio Observatory	DA	1420	615	2
Dwingeloo-NRAO	DW	1417	188	2.3
Arecibo	AO	430	25	—

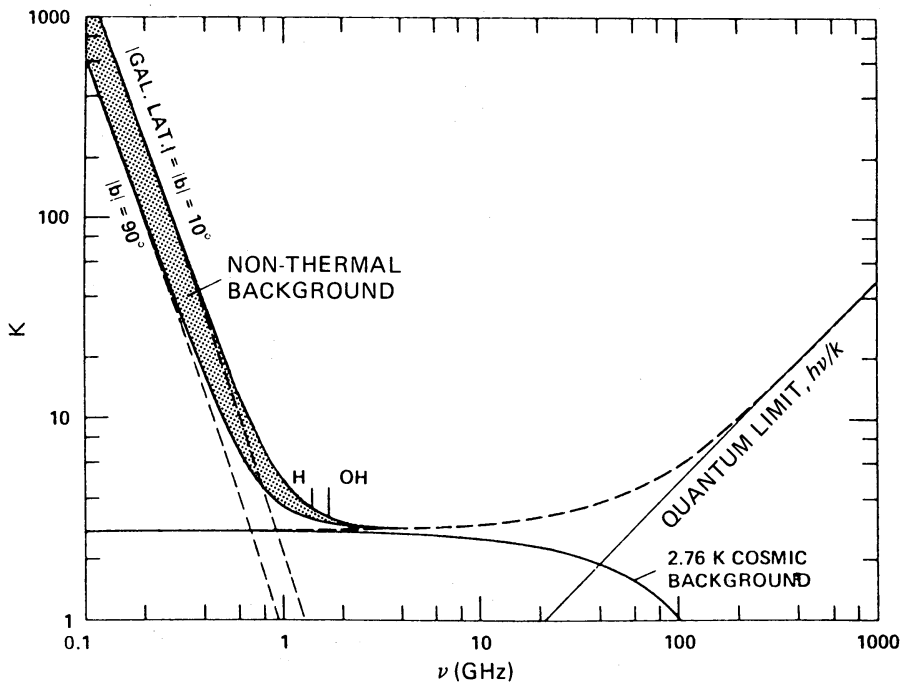
[a] 1 jansky (Jy) = $10^{-26}\,\mathrm{Wm}^{-2}\,\mathrm{Hz}^{-1}$.
(Adapted from Weinberg, S., *Gravitation and Cosmology*, John Wiley and Sons, 1972.)

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Measurement of the surface brightness, B_ν of the cosmic background radiation. The spectrum of a 2.75 K blackbody emitter is also shown. (Courtesy of T. Wilkinson, Princeton University.)



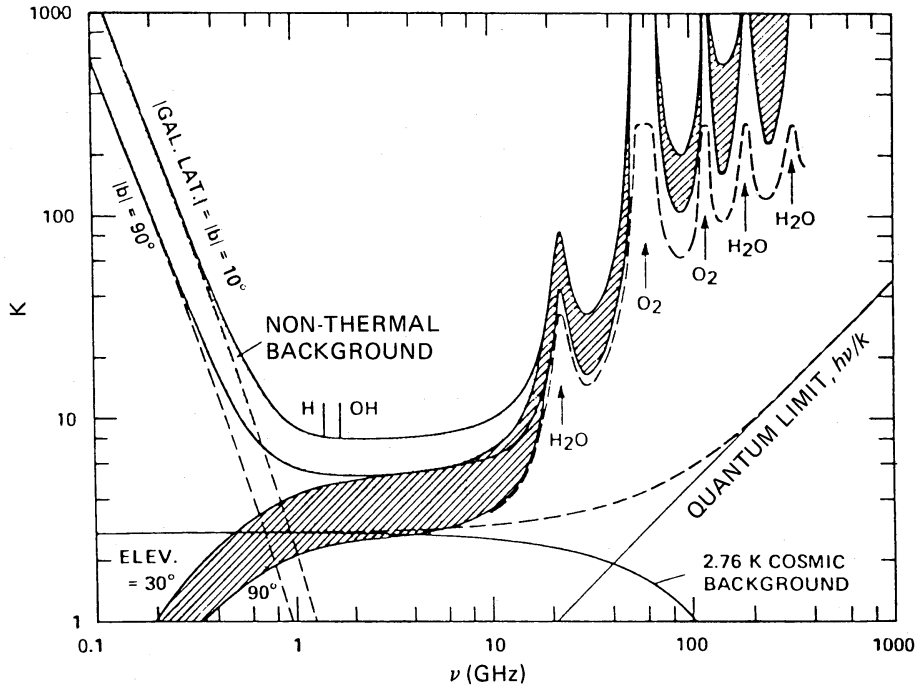
Free space microwave window. (From NASA SP-419, *The Search for Extraterrestrial Intelligence, SETI.*)



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Microwave background (*cont.*)

Terrestrial microwave window. (From NASA SP-419, *op. cit.*)



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Selected discrete radio sources

Source	α 1950	δ 1950	Spectral flux density (fu)[a] 100 (MHz)	1000 (MHz)	10 000 (MHz)	Size (arcmin)	Log distance (pc)	Identification
Cas B	00^h23^m	+63° 52′	250	56		7	3.5	Tycho SN I, 1572
And A	00 40	+41 00	190	60		140	5.8	Andr. Galaxy, M31
	00 54	−73	400	100				
	02 22	+61 51	100	100				Mult. H II region OH em
Per A	03 16	+41 19	130	20		2	7.9	Seyfert Galaxy, NGC 1275
For A	03 20	−37 22	400	120		Large		Pec. Galaxy, NGC 1316?
Per 3C 123	04 34	+29 34	280	70		1		
	04 58	+46 26	120	150		60 + *h*(*alo*)		Gal. Nebula SN II
Pic A	05 18	−45 49	400	80		Large		
	05 21	−69	3000	700				
Tau A	05 32	+21 59	1700	955	560	5	3.3	Crab Nebula SN I 1054
Ori Neb.	05 33	−05 24	40	340	400	10	2.7	Orion Nebula, M42
Gem 3C 157	06 15	+22 38	400	180		30 + *h*	3.1	IC 443, SN II
Mon	06 29	+04 54	400	250		70	3.0	Rosette Nebula
Pup A	08 21	−42 58	600	150		40 + *h*	2.7	
	08 32	−45 37	500	200				Vela X (?)
Hya A	09 16	−11 53	400	60	10	1	8.4	Pec. Galaxy
Car	10 43	−59 30	500	800			3.1	Carina Nebula
3C 273	12 27	+02 19	140	50		1		Quasar
Vir A	12 28	+12 40	1800	263	40	5	7.1	Pec. Jet Galaxy, M87
Cen A	13 22	−42 46	3000	2000		5 + *h*	6.8	Pec. Galaxy, NGC 5128
Cen B	13 30	−60	600	80				

Selected discrete radio sources (*cont.*)

Source	α 1950	δ 1950	Spectral flux density (fu)[a] 100 (MHz)	1000 (MHz)	10 000 (MHz)	Size (arcmin)	Log dist. (pc)	Identification
Boo 3C 295	14^h10^m	+52°26′	100	30		1		Distant galaxy
Tr A	16 10	−60 47	800	80				
3C 338	16 27	+39 39	80	7		1		4 Galaxies, NGC 6161
Her A	16 48	+05 04	700	70	8	3	8.6	Pec. Galaxy
	17 11	−38 25	400	100				
2C 1473	17 16	−00 55	400	80	10	4		Galaxy
	17 22	−34 14	400	400	500			
2C 1485	17 28	−21 20	80	20		1	2.9	Kepler SN I, 1604
Sgr A	17 43	−28 56	4000	2000	200	70	3.9	Galactic center
Trifid	17 58	−23 24	800	300			3.0	Galactic nebula, M20
Lagoon	18 01	−24 22	70	150			3.1	Galactic nebula, M8
	18 02	−21 30	200	150				
Omega	18 18	−16 10	200	800	500	10	3.2	Galactic nebula, M17
	18 45	−02 06	500	300	250			
3C 392	18 54	+01 16	500	210		16		Shell source, SN
3C 398	19 08	+09 01	40	70		3		SN II region, OH em
3C 400	19 21	+14 20	400	400		60		
Cyg A	19 58	+40 35	13 800	2340	163	1.2	8.5	Radio galaxy
Cyg X	20 21	+40 12	200	400		60		

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Cyg X	20 34	+41 40	150	500	50	40	3.1	? γ Cyg complex
2C 1725	20 44	+50	400	150		100		SN II
Cyg Loop	20 49	+30	400	200		150	2.7	Loops SN II
America	20 52	+43 54	700	500		150	2.9	Galactic nebula
3C 446	22 23	−05 12	30	6				Quasar
Cas A	23 21	+58 32	19 500	3300	490	4	3.4	Galactic nebula SN II

[a] Flux unit, fu = 10^{-26} W m^{-2}Hz^{-1}.
(After Allen, C. W., *Astrophysical Quantities*, The Athlone Press, 1973.)

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The brightest radio sources visible in the northern hemisphere (based on observations at the 20 cm wavelength)

Name	α 1950	δ 1950	Intensity (fu)	Identification
3C 10	$00^h22^m37^s$	63° 51′ 41″	44	Supernova remnant[a] – Tycho's supernova
3C 20	00 40 20	51 47 10	12	Galaxy
3C 33	01 06 13	13 03 28	13	Elliptical Galaxy
3C 48	01 34 50	32 54 20	16	Quasar
3C 58	02 01 52	64 35 17	34	Supernova remnant[a]
3C 84	03 16 30	41 19 52	14	Seyfert Galaxy
Fornax A	03 20 42	−37 25 00	115	Spiral Galaxy
NRAO 1560	04 00 00	51 08 00	26	
NRAO 1650	04 07 08	50 58 00	19	
3C 111	04 15 02	37 54 29	15	
3C 123	04 33 55	29 34 14	47	Galaxy
Pictor A	05 18 18	−45 49 39	66	D Galaxy[b]
3C 139.1	05 19 21	33 25 00	40	Emission nebula[a]
NRAO 2068	05 21 13	−36 30 19	19	N Galaxy[c]
3C 144	05 31 30	21 59 00	875	Supernova remnant[a] – Crab Nebula–Taurus A
3C 145	05 32 51	−05 25 00	520	Emission nebula[a] – Orion A–NGC 1976
3C 147	05 38 44	49 49 42	23	Quasar
3C 147.1	05 39 11	−01 55 42	65	Emission nebula[a] – Orion B–NGC 2024
3C 153.1	06 06 53	20 30 40	29	Emission nebula[a]
3C 161	06 24 43	−05 51 14	19	
3C 196	08 09 59	48 22 07	14	Quasar
3C 218	09 15 41	−11 53 05	43	D Galaxy[b]
3C 270	12 16 50	06 06 09	18	Elliptical Galaxy
3C 273	12 26 33	02 19 42	46	Quasar
3C 274	12 28 18	12 40 02	198	Elliptical Galaxy – M87–Virgo A
3C 279	12 53 36	−5 31 08	11	Quasar
Centaurus A	13 22 32	−42 45 24	1330	Elliptical Galaxy – NGC 5128
3C 286	13 28 50	30 45 58	15	Quasar
3C 295	14 09 33	52 26 13	23	D Galaxy[b]
3C 348	16 48 41	05 04 36	45	D Galaxy[b]
3C 353	17 17 56	−00 55 53	57	D Galaxy[b]
3C 358	17 27 41	−21 27 11	15	Supernova remnant[a] – Kepler's supernova
3C 380	18 28 13	48 42 41	14	Quasar
NRAO 5670	18 28 51	−02 06 00	12	
NRAO 5690	18 32 41	−07 22 00	90	
NRAO 5720	18 35 33	−06 50 18	30	
3C 387	18 38 35	−05 11 00	51	

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The brightest radio sources visible in the northern hemisphere (*cont.*)

Name	α 1950	δ 1950	Intensity (fu)	Identification
NRAO 5790	$18^h43^m30^s$	−02°46′ 39″	19	
3C 390.2	18 44 25	−02 33 00	80	
3C 390.3	18 45 53	79 42 47	12	N Galaxy
3C 391	18 46 49	−00 58 58	21	
NRAO 5840	18 50 52	01 08 18	15	
3C 392	18 53 38	01 15 10	171	Supernova remnant[a]
NRAO 5890	18 59 16	01 42 31	14	
3C 396	19 01 39	05 21 54	14	
3C 397	19 04 57	07 01 50	29	
NRAO 5980	19 07 55	08 59 09	47	
3C 398	19 08 43	08 59 49	33	
NRAO 6010	19 11 59	11 03 30	10	
NRAO 6020	19 13 19	10 57 00	35	
NRAO 6070	19 15 47	12 06 00	11	
3C 400	19 20 40	14 06 00	576	
NRAO 6107	19 32 20	−46 27 32	13	
3C 403.2	19 52 19	32 46 00	75	
3C 405	19 57 44	40 35 46	1495	D Galaxy[b] – Cygnus A
NRAO 6210	19 59 49	33 09 00	55	
3C 409	20 12 18	23 25 42	14	
3C 410	20 18 05	29 32 41	10	
NRAO 6365	20 37 14	42 09 07	20	Emission nebula[a]
NRAO 6435	21 04 25	−25 39 06	12	Elliptical Galaxy
NRAO 6500	21 11 06	52 13 00	46	
3C 433	21 21 31	24 51 18	12	D Galaxy[b]
3C 434.1	21 23 26	51 42 14	12	
NRAO 6620	21 27 41	50 35 00	37	
NRAO 6635	21 34 05	00 28 26	10	Quasar
3C 452	22 43 33	39 25 28	11	Elliptical Galaxy
3C 454.3	22 51 29	15 52 54	11	Quasar
3C 461	23 21 07	58 32 47	2477	Supernova remnant[a] – Cassiopeia A

$fu = 10^{-26}\,W\,m^{-2}\,Hz^{-1}$.

[a] Supernova remnants and emission nebulae lie within our own galaxy.

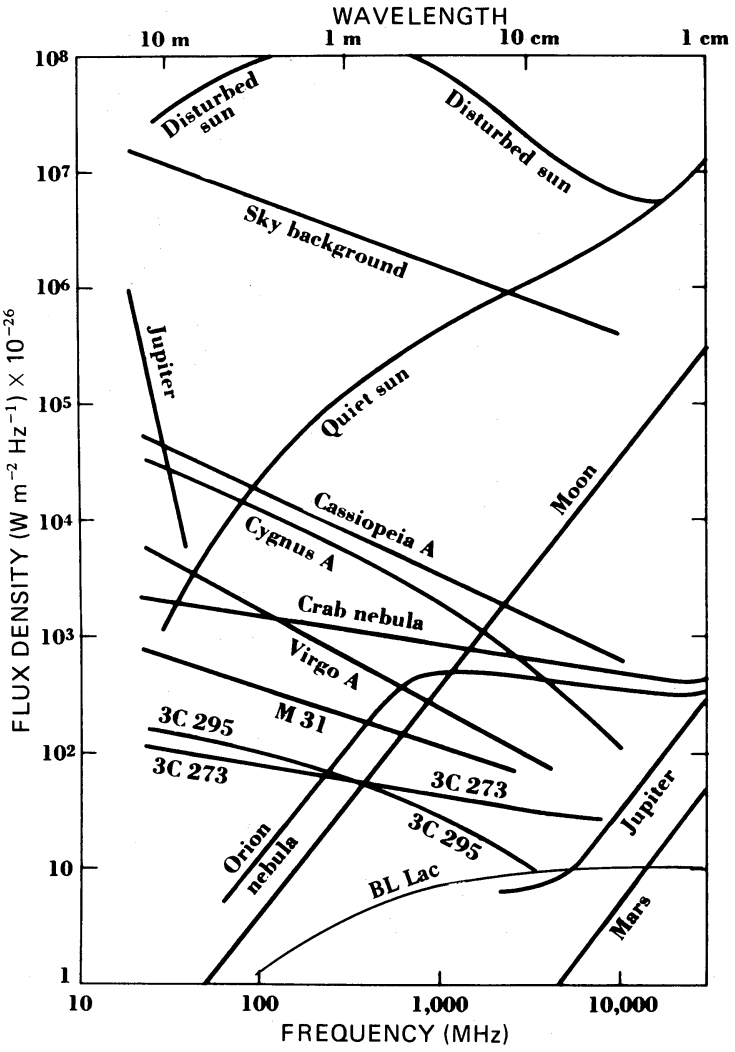
[b] Galaxy refers to a Dumbell-shaped galaxy.

[c] N Galaxy refers to a galaxy with a bright nucleus.

(Adapted from Verschuur, G. L., *The Invisible Universe*, Springer-Verlag, 1974.)

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Spectra of typical radio sources. (Adapted from Kraus, J. D., *Radio Astronomy*, McGraw-Hill Co., 1966.)



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Radio flux calibrators*

(a) *Spectral parameters of telescope calibrators*

Source	Frequency interval	Spectral parameters $\log S[\mathrm{Jy}] = a + b \cdot \log \nu[\mathrm{MHz}] + c \cdot \log^2 \nu[\mathrm{MHz}]$					
		a		b		c	
3C 48	405 MHz...15 GHz	2.345	±0.030	+0.071	±0.001	−0.138	±0.001
3C 123	405 MHz...15 GHz	2.921	±0.025	−0.002	±0.0001	−0.124	±0.001
3C 147	405 MHz...15 GHz	1.766	±0.017	+0.447	±0.006	−0.184	±0.001
3C 161	405 MHz...10.7GHz	1.633	±0.016	+0.498	±0.008	−0.194	±0.001
3C 218	405 MHz...10.7GHz	4.497	±0.038	−0.910	±0.011	—	
3C 227	405 MHz...15 GHz	3.460	±0.055	−0.827	±0.016	—	
3C 249.1	405 MHz...15 GHz	1.230	±0.027	+0.288	+0.007	−0.176	±0.003
3C 286	405 MHz...15 GHz	1.480	±0.018	+0.292	±0.006	−0.124	±0.001
3C 295	405 MHz...15 GHz	1.485	±0.013	+0.759	±0.009	−0.255	±0.001
3C 348	405 MHz...10.7GHz	4.963	±0.045	−1.052	±0.014	—	
3C 353	405 MHz...10.7GHz	2.944	±0.031	−0.034	±0.001	−0.109	±0.001
DR 21	7 GHz...31 GHz	1.81	±0.05	−0.122	±0.010	—	—
NGC 7027	10 GHz...31 GHz	1.32	±0.08	−0.127	±0.012	—	—

(b) *Characteristics, position, and flux densities of telescope calibrators*

Source	α 1950 [h m s]	δ 1950 [° ′ ″]	b^{II} [°]	S_{1400} [Jy]	S_{1665} [Jy]	S_{2700} [Jy]	S_{5000} [Jy]	S_{8000} [Jy]	S_{10700} [Jy]	S_{15000} [Jy]	S_{22235} [Jy]	Spec.	Ident.	Polar. (at 5 GHz) [%]	Ang. size (at 1.4 GHz) [″]
3C 48	01 34 49.8	+32 54 20	−29	15.9	13.9	9.20	5.24	3.31	2.46	1.72	1.11	C^-	QSS	5	<1
3C 123	04 33 55.2	+29 34 14	−12	48.7	42.4	28.5	16.5	10.6	7.94	5.63	3.71	C^-	GAL	2	20
3C 147	05 38 43.5	+49 49 42	+10	22.4	19.8	13.6	7.98	5.10	3.80	2.65	1.71	C^-	QSS	<1	<1
3C 161	06 24 43.1	−05 51 14	− 8	19.0	16.8	11.4	6.62	4.18	3.09	2.14	—	C^-	GAL	5	<3
3C 218	09 15 41.5	−11 53 06	+25	43.1	36.8	23.7	13.5	8.81	6.77	—	—	S	GAL	1	core 25 halo 200
3C 227	09 45 07.8	+07 39 09	+42	7.21	6.25	4.19	2.52	1.71	1.34	1.02	0.73	S	GAL	7	180
3C 249.1	11 00 25.0	+77 15 11	+39	2.48	2.14	1.40	0.77	0.47	0.34	0.23	—	S	QSS	—	15
3C 274	12 28 17.7	+12 39 55	+74	214	184	122	71.9	48.1	37.5	28.1	20.0	S	GAL	1	halo 400[a]
3C 286	13 28 49.7	+30 45 58	+81	14.8	13.6	10.5	7.30	5.38	4.40	3.44	2.55	C^-	QSS	11	<5
3C 295	14 09 33.5	+52 26 13	+61	22.3	19.2	12.2	6.36	3.65	2.53	1.61	0.92	C^-	GAL	0.1	4
3C 348	16 48 40.1	+05 04 28	+29	45.0	37.5	22.6	11.8	7.19	5.30	—	—	S	GAL	8	115[b]
3C 353	17 17 54.6	−00 55 55		57.3	50.5	35.0	21.2	14.2	10.9	—	—	C^-	GAL	5	150
DR 21	20 37 14.2	+42 09 07	+ 1	—	—	—	—	21.6	20.8	20.0	19.0	*Th*	HII	—	20[c]
NGC 7027[d]	21 05 09.4	+42 02 03	− 3	1.35	1.65	3.5	5.7	—	6.43	6.16	5.86	*Th*	PN	<1	10

[a] Halo has steep spectral index, so for $\lambda \leqslant 6$ cm, more than 90% of the flux is in the core.
[b] Angular distance between the two components.
[c] Angular size at 2 cm, but consists of 5 smaller components.
[d] Data up to 5 GHz are the direct measurements, not calculated from fit.
Systematic errors over the frequency range 0.4–15 GHz are less than 4%.
(Taken from Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., Witzel, A., *Astron. Astrophys.* **61**, 99 (1977).)

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The Earth's atmosphere (>25 MHz)

$$S(z) = S_0 d^{-X(z)}$$

where

$S(z)$ = the flux measured at zenith distance z,
S_0 = flux outside the atmosphere,
d = the attenuation at the zenith for airmass 1,
$X(z)$ = relative airmass in units of the airmass at the zenith.

For a plane parallel atmospheric model:

$$X(z) = \sec z = \frac{1}{\cos z}$$

Taking into account the Earth's and troposphere's curvature:

$$X(z) = \frac{1}{H} \int_R^{R+H} \frac{\rho(r)/\rho(R)}{\left[1 - \left(\frac{R}{r}\frac{n_0}{n}\right)^2 \sin^2 z\right]^{1/2}} \mathrm{d}r$$

where

R = radius of Earth,
H = height of atmosphere,
$\rho(r)$ = gas density of the atmosphere at radius r,
n = index of refraction at radius r.
n_0 = index of refraction at radius R.

Up to $X = 5.2$ the following equation gives $X(z)$, with an error less than 6.4×10^{-4}.

$$X(z) = -0.0045 + 1.006\,72 \sec z - 0.002\,234 \sec^2 z - 0.000\,624\,7 \sec^3$$

(After K. Rohlfs, *Tools of Radio Astronomy*, Springer-Verlag, 1986.)

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Interplanetary medium

The electron density as a function of distance from the Sun:

$$\mathcal{N}_e = [1.55r^{-6} + 2.99r^{-16}] \times 10^{14} \quad (\mathrm{m}^{-3}), \quad r < 4,$$

where r is the radial distance from the Sun in units of the solar radius,

$$\mathcal{N}_e = 5 \times 10^{11} r^{-2} \quad (\mathrm{m}^{-3}), \quad 4 < r < 20.$$

The scattering angle due to the interplanetary medium may be approximated by:

$$\theta_s \simeq 50\left(\frac{\lambda}{p}\right)^2 \quad (\text{arcmin}),$$

where λ is in meters and p, the solar impact parameter, is in solar radii.

Interstellar medium (delay and Faraday rotation)

The smooth, ionized component of the interstellar medium of the Galaxy affects propagation by introducing delay and Faraday rotation. The time of arrival of a pulse of radiation is:

$$t_p = \int_0^L \frac{dz}{v_g},$$

where L is the propagation path, v_g is the group velocity;

$$\frac{dt_p}{dv} \simeq -\frac{e^2}{4\pi\varepsilon_0 mcv^3} \int_0^L \mathcal{N}_e \, dz.$$

The integral of $\mathcal{N}_e$ over the path length is called the *dispersion measure*,

$$D_m = \int_0^L \mathcal{N}_e \, dz,$$

The magnetic field of the Galaxy causes Faraday rotation of the polarization plane of radiation from extragalactic radio sources.

$$\Delta\psi = \lambda^2 R_m,$$

where R_m is the *rotation measure* given by

$$R_m = 8.1 \times 10^5 \int \mathcal{N}_e B_\parallel \, dz.$$

Here R_m is in radians per square meter, λ is in meters, $B_\parallel$ is the longitudinal component of magnetic field in gauss (1 gauss $= 10^{-4}$ tesla), $\mathcal{N}_e$ is in centimeters^{-3}, dz is in parsecs (pc) (1 pc $= 3.1 \times 10^{16}$ m), and $\Delta\psi$ is the change in position angle of the electric field:

$$B_\parallel \simeq 2\mu G,$$

$$R_m \simeq -18|\cot b| \cos(l - 94°),$$

where l and b are the galactic longitude and latitude, respectively.

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Interstellar medium (scintillation)

Approximate formulae for interstellar scintillation:

$$\theta_s \simeq 7.5\lambda^{11/5} \quad \text{(arcsec)}, \quad |b| \leqslant 6^\circ$$

$$\simeq 0.5|\sin b|^{-3/5}\lambda^{11/5} \quad \text{(arcsec)}, \quad 0^\circ < |b| < 3^\circ\text{–}5^\circ$$

$$\simeq 13|\sin b|^{-3/5}\lambda^{11/5} \quad \text{(milliarcsec)}, \quad |b| \geqslant 3^\circ\text{–}5^\circ$$

$$\simeq \frac{15}{\sqrt{(|\sin b|)}}\lambda^2 \quad \text{(milliarcsec)}, \quad |b| > 15^\circ,$$

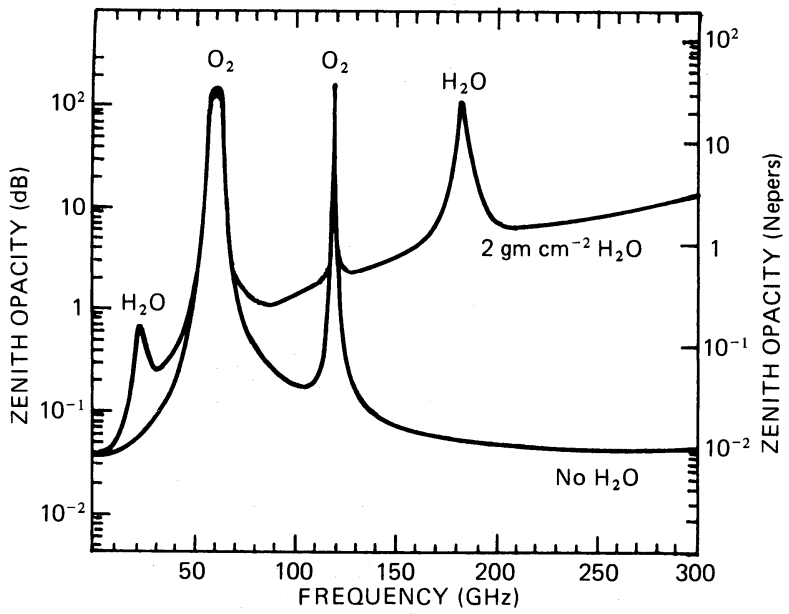
where b is the galactic latitude and λ is the wavelength in meters.

The accuracy of the approximations above decreases with decreasing $|b|$. In particular, the scattering angle at low latitudes, $|b| < 1^\circ$, can take on a large range of values.

(Adapted from Thompson, A. R., Moran, J. M. & Swenson, G. W., *Interferometry and Synthesis in Radio Astronomy*, Wiley-Interscience, 1986.)
(For propagation effects in the neutral lower atmosphere, see Thompson *et al.*, *op. cit.*)

Atmospheric opacity

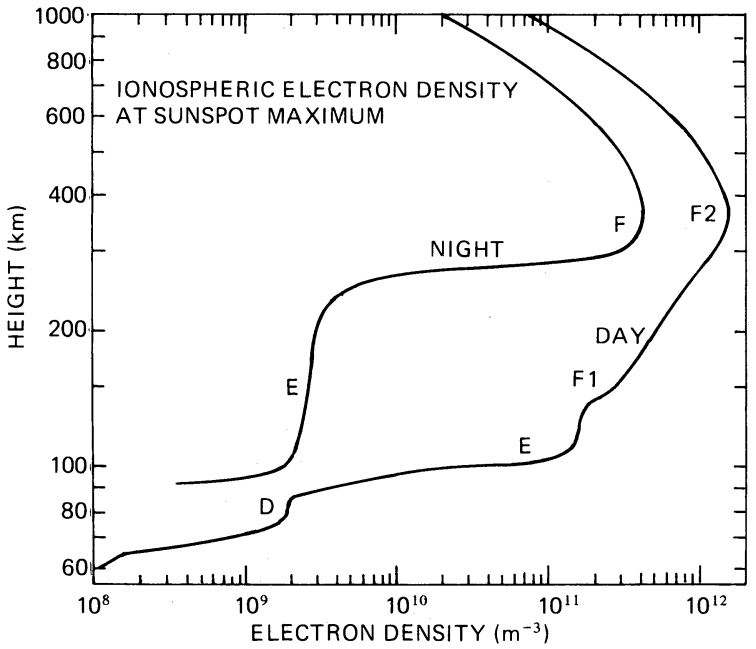
Atmospheric zenith opacity. The absorption from narrow ozone lines has been omitted. (From Thompson, A. R. *et al.*, *op. cit.*)



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Ionospheric electron density

Idealized electron density distribution in the Earth's ionosphere. The curves drawn indicate the densities to be expected at sunspot maximum in temperate latitudes. (From Evans & Hagfors, 1968.)



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An incomplete list of astrophysically important spectral radio features†

Chemical name	Chemical formula	Transition	Frequency[a] (GHz)
Deuterium[b]	D		0.327
Hydrogen	H	$1^2S_{1/2}, F = 1$–0	1.420
Hydroxyl radical	OH	$^2\Pi_{3/2}$, $J = 3/2$, $F = 1$–2	1.612
	OH	$^2\Pi_{3/2}$, $J = 3/2$, $F = 1$–1	1.665
	OH	$^2\Pi_{3/2}$, $J = 3/2$, $F = 2$–2	1.667
	OH	$^2\Pi_{3/2}$, $J = 3/2$, $F = 2$–1	1.721
Formaldehyde	H_2CO	1_{10}–1_{11}, hyperfine structure	4.830
Water	H_2O	6_{16}–5_{23}, hyperfine structure	22.235
Ammonia	NH_3	1,1–1,1, hyperfine structure	23.694
	NH_3	2,2–2,2, hyperfine structure	23.723
	NH_3	3,3–3,3, hyperfine structure	23.870
Silicon monoxide	SiO	$v = 2$, $J = 1$–0	42.820
	SiO	$v = 1$, $J = 1$–0	43.122
	SiO	$v = 1$, $J = 2$–1	86.243
Hydrogen cyanide	HCN	$J = 1$–0, hyperfine structure	88.631
Formyl ion	HCO^+	$J = 1$–0	89.189
Carbon monoxide	$^{12}C^{18}O$	$J = 1$–0	109.782
Carbon monoxide	$^{13}C^{16}O$	$J = 1$–0	110.201
Carbon monoxide	$^{12}C^{16}O$	$J = 1$–0	115.271
Carbon monoxide	$^{12}C^{16}O$	$J = 2$–1	230.538
Carbon	C	$^3P_1$–$^3P_0$	492.162

[a] λ (m) $= 0.3/f$ (GHz).
[b] Not yet found in radio spectra.
† Many hundreds of lines have been detected for more than 70 molecules.
(Adapted from Thompson, A. R., Moran, J. M. & Swenson, G. W., *Interferometry and Synthesis in Radio Astronomy*, Wiley-Interscience, 1986.)

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