

# **Recommendation ITU-R RA.314-11**

## **(12/2023)**

RA Series: Radio astronomy

### **Preferred frequency bands for radio astronomical measurements below 1 THz**

## Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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Series	Title
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<b>BR</b>	Recording for production, archival and play-out; film for television
<b>BS</b>	Broadcasting service (sound)
<b>BT</b>	Broadcasting service (television)
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<b>M</b>	Mobile, radiodetermination, amateur and related satellite services
<b>P</b>	Radiowave propagation
<b>RA</b>	<b>Radio astronomy</b>
<b>RS</b>	Remote sensing systems
<b>S</b>	Fixed-satellite service
<b>SA</b>	Space applications and meteorology
<b>SF</b>	Frequency sharing and coordination between fixed-satellite and fixed service systems
<b>SM</b>	Spectrum management
<b>SNG</b>	Satellite news gathering
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<b>V</b>	Vocabulary and related subjects

*Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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## RECOMMENDATION ITU-R RA.314-11

**Preferred frequency bands for radio astronomical measurements below 1 THz**

(Question ITU-R 145/7)

(1953-1956-1959-1966-1970-1974-1978-1982-1986-1990-1992-2002-2003-2023)

**Scope**

This Recommendation provides information regarding the preferred frequency bands for radio astronomical measurements up to 1 000 GHz. Tables 1 and 2 list the frequency bands associated with atomic and molecular transitions; Table 3 lists the frequency bands preferred for observations of radio continuum emission; Table 4 lists the frequency bands for several specific applications of redshifted neutral hydrogen. Figures in the Annex illustrate the natural processes that dictate the preferred frequency bands for radio astronomy.

**Keywords**

Radio astronomy, fundamental physics, atomic and molecular transitions, continuum emission, atmospheric transparency

The ITU Radiocommunication Assembly,

*considering*

- a) that the development of radio astronomy has led to major technological advances, particularly in receiving techniques and to improved knowledge of fundamental radio-noise limitations of great importance to radiocommunication, and promises further important results;
- b) that the advancement of radio astronomy requires the protection of certain frequency bands from interference;
- c) that the International Astronomical Union (IAU) is maintaining and updating the list of spectral lines of the greatest importance to radio astronomy;
- d) that radio astronomers study spectral lines both in bands allocated to the radio astronomy service and, as far as spectrum usage by other services allows, outside the allocated bands, and that this has resulted in the detection of thousands of spectral lines as illustrated in Fig. 1 of Annex 1;
- e) that account should be taken of the Doppler shifts of the lines, due to the relative motion of source and observer;
- f) that the observed frequencies of highly redshifted (Doppler-shifted) atomic or molecular spectral lines from the distant Universe are significantly lower than their rest frequencies, as illustrated in Table 4 and Fig. 3 of Annex 1;
- g) that certain frequency bands have been allocated for continuum observations, and that the exact positions of these bands in the spectrum are not of critical importance, as illustrated in Fig. 4 of Annex 1, but that their centre frequencies should be in the ratio not more than two to one, taking the width of relevant atmospheric windows (see Fig. 1 of Annex 1) into account;
- h) that radio astronomers have made useful astronomical observations from the Earth's surface in all available atmospheric windows (see Fig. 1 of Annex 1) ranging from 2 MHz to 1 000 GHz and above;
- i) that the technique of space radio astronomy, which involves the use of radio telescopes on space platforms, provides access to the entire radio spectrum above about 10 kHz, including parts of the spectrum not accessible from the Earth due to absorption in the atmosphere;

j) that some types of high-resolution interferometric observations require simultaneous reception, at the same radio frequency, by receiving systems located in different countries, on different continents, or on space platforms;

k) that world administrative radio conferences and world radiocommunication conferences have made improved frequency allocations for radio astronomy, but that protection in many bands, particularly those shared with other services, may still need careful planning,

*noting*

that preferred bands between 1 and 3 THz are contained in Recommendation ITU-R RA.1860,

*recommends*

1 that administrations should afford all practicable protection to the frequencies used by radio astronomers in their own and neighbouring countries;

2 that particular attention should be given to securing or maintaining adequate protection for the frequency bands listed in Tables 1 and 2, which contain rest frequencies and Doppler-shifted frequencies of the astrophysically most important spectral lines identified by the General Assembly of the IAU, and in Table 3, which contains the frequency bands allocated to the radio astronomy service that are preferred for continuum observations;

3 that administrations be asked to provide assistance in the coordination of observations of spectral lines in bands not allocated to radio astronomy.

TABLE 1

**Radio frequency lines of the greatest importance to radio astronomy at frequencies below 275 GHz**

Substance	Rest frequency	Suggested minimum band	Notes <sup>(1)</sup>
Deuterium (D I)	327.384 MHz	327.0-327.7 MHz	
Hydrogen (H I)	1 420.406 MHz	1 370.0-1 427.0 MHz	(2), (3)
Hydroxyl radical (OH)	1 612.231 MHz	1 606.8-1 613.8 MHz	(4)
Hydroxyl radical (OH)	1 665.402 MHz	1 659.8-1 667.1 MHz	(4)
Hydroxyl radical (OH)	1 667.359 MHz	1 661.8-1 669.0 MHz	(4)
Hydroxyl radical (OH)	1 720.530 MHz	1 714.8-1 722.2 MHz	(3), (4)
Methylidyne (CH)	3 263.794 MHz	3 252.9-3 267.1 MHz	(3), (4)
Methylidyne (CH)	3 335.481 MHz	3 324.4-3 338.8 MHz	(3), (4)
Methylidyne (CH)	3 349.193 MHz	3 338.0-3 352.5 MHz	(3), (4)
Formaldehyde (H <sub>2</sub> CO)	4 829.660 MHz	4 813.6-4 834.5 MHz	(3), (4)
Methanol (CH <sub>3</sub> OH)	6 668.518 MHz	6 661.8-6 675.2 MHz	(3)
Helium ( <sup>3</sup> He <sup>+</sup> )	8 665.650 MHz	8 657.0-8 674.3 MHz	(3), (6)
Methanol (CH <sub>3</sub> OH)	12.178 GHz	12.17-12.19 GHz	(3), (6)
Formaldehyde (H <sub>2</sub> CO)	14.488 GHz	14.44-14.50 GHz	(3), (4)
Cyclopropenylidene (C <sub>3</sub> H <sub>2</sub> )	18.343 GHz	18.28-18.36 GHz	(3), (4), (6)
Water vapour (H <sub>2</sub> O)	22.235 GHz	22.16-22.26 GHz	(3), (4)
Ammonia (NH <sub>3</sub> )	23.694 GHz	23.61-23.71 GHz	(4)
Ammonia (NH <sub>3</sub> )	23.723 GHz	23.64-23.74 GHz	(4)
Ammonia (NH <sub>3</sub> )	23.870 GHz	23.79-23.89 GHz	(4)

TABLE 1 (*continued*)

Substance	Rest frequency	Suggested minimum band	Notes <sup>(1)</sup>
Sulphur monoxide (SO)	30.002 GHz	29.97-30.03 GHz	(6)
Methanol (CH <sub>3</sub> OH)	36.169 GHz	36.13-36.21 GHz	(6)
Silicon monoxide (SiO)	42.519 GHz	42.47-42.57 GHz	(6), (8)
Silicon monoxide (SiO)	42.821 GHz	42.77-42.86 GHz	
Silicon monoxide (SiO)	43.122 GHz	43.07-43.17 GHz	
Silicon monoxide (SiO)	43.424 GHz	43.37-43.47 GHz	
Dicarbon monosulphide (CCS)	45.379 GHz	45.33-45.44 GHz	(6)
Carbon monosulphide (CS)	48.991 GHz	48.94-49.04 GHz	
Molecular oxygen (O <sub>2</sub> )	61.1 GHz	56.31-63.06 GHz	(5), (6), (7)
Deuterated water vapour (HDO)	80.578 GHz	80.50-80.66 GHz	
Cyclopropenylidene (C <sub>3</sub> H <sub>2</sub> )	85.339 GHz	85.05-85.42 GHz	
Silicon monoxide (SiO)	86.243 GHz	86.16-86.33 GHz	
Formylium (H <sup>13</sup> CO <sup>+</sup> )	86.754 GHz	86.66-86.84 GHz	
Silicon monoxide (SiO)	86.847 GHz	86.76-86.93 GHz	
Ethynyl radical (C <sub>2</sub> H)	87.3 GHz	87.21-87.39 GHz	(5)
Hydrogen cyanide (HCN)	88.632 GHz	88.34-88.72 GHz	(4)
Formylium (HCO <sup>+</sup> )	89.189 GHz	88.89-89.28 GHz	(4)
Hydrogen isocyanide (HNC)	90.664 GHz	90.57-90.76 GHz	
Diazenylium (N <sub>2</sub> H <sup>+</sup> )	93.174 GHz	93.07-93.27 GHz	
Carbon monosulphide (CS)	97.981 GHz	97.65-98.08 GHz	(4)
Sulphur monoxide (SO)	99.300 GHz	99.98-100.18 GHz	
Methyl acetylene (CH <sub>3</sub> C <sub>2</sub> H)	102.5 GHz	102.39-102.60 GHz	(5)
Methanol (CH <sub>3</sub> OH)	107.014 GHz	106.91-107.12 GHz	
Carbon monoxide (C <sup>18</sup> O)	109.782 GHz	109.67-109.89 GHz	
Carbon monoxide ( <sup>13</sup> CO)	110.201 GHz	109.83-110.31 GHz	(4)
Carbon monoxide (C <sup>17</sup> O)	112.359 GHz	112.25-112.47 GHz	
Cyano radical (CN)	113.5 GHz	113.39-113.61 GHz	(5)
Carbon monoxide (CO)	115.271 GHz	114.88-115.39 GHz	(4)
Molecular oxygen (O <sub>2</sub> )	118.750 GHz	118.63-118.87 GHz	(6), (7)
Formaldehyde (H <sub>2</sub> <sup>13</sup> CO)	137.450 GHz	137.31-137.59 GHz	
Formaldehyde (H <sub>2</sub> CO)	140.840 GHz	140.69-140.98 GHz	
Carbon monosulphide (CS)	146.969 GHz	146.82-147.12 GHz	
Nitric oxide (NO)	150.4 GHz	149.95-150.85 GHz	(5)
Methanol (CH <sub>3</sub> OH)	156.602 GHz	156.45-156.76 GHz	
Water vapour (H <sub>2</sub> O)	183.310 GHz	183.12-183.50 GHz	
Carbon monoxide (C <sup>18</sup> O)	219.560 GHz	219.34-219.78 GHz	
Carbon monoxide ( <sup>13</sup> CO)	220.399 GHz	219.67-220.62 GHz	(4)
Cyano radical (CN)	226.6 GHz	226.37-226.83 GHz	(5)
Cyano radical (CN)	226.8 GHz	226.57-227.03 GHz	(5)

TABLE 1 (*end*)

Substance	Rest frequency	Suggested minimum band	Notes <sup>(1)</sup>
Carbon monoxide (CO)	230.538 GHz	229.77-230.77 GHz	(4)
Carbon monosulphide (CS)	244.953 GHz	244.72-245.20 GHz	
Nitric oxide (NO)	250.6 GHz	250.35-250.85 GHz	(5)
Ethynyl radical (C <sub>2</sub> H)	262.0 GHz	261.74-262.26 GHz	(5)
Hydrogen cyanide (HCN)	265.886 GHz	265.62-266.15 GHz	
Formylium (HCO <sup>+</sup> )	267.557 GHz	267.29-267.83 GHz	
Hydrogen isocyanide (HNC)	271.981 GHz	271.71-272.25 GHz	

- (1) If Notes <sup>(2)</sup> or <sup>(4)</sup> are not listed, the band limits are the Doppler-shifted frequencies corresponding to radial velocities of  $\pm 300$  km/s (consistent with line radiation occurring in the Milky Way Galaxy).
- (2) An extension to lower frequency of the allocation of 1 400-1 427 MHz is required to allow for the higher Doppler shifts for H I observed in distant galaxies. Additional preferred frequency ranges for redshifted neutral hydrogen for relevant astronomical epochs are listed in Table 4.
- (3) The current international allocation is not primary and/or does not meet bandwidth requirements. See the Radio Regulations (RR) for more detailed information.
- (4) Because these line frequencies are also being used for observing galaxies other than the Milky Way Galaxy, the listed bandwidths include Doppler shifts corresponding to radial velocities of up to 1 000 km/s. Some lines of the most abundant molecules, as well as H I, have been detected in galaxies with very large recession velocities caused by the expansion of the Universe, which results in observed frequencies substantially lower than the rest-frame emission frequency (see Fig. 3).
- (5) There are several closely spaced lines associated with these molecules. The listed bands are wide enough to permit observations of all lines.
- (6) This line frequency is outside of bands allocated to the radio astronomy service.
- (7) These lines are observable only outside the Earth's atmosphere by, for example, using receivers located on high-altitude balloons, aircraft, satellites, or other non-terrestrial platforms (see also RR Article 22, Section V).
- (8) A portion of the "suggested minimum band" for this line extends outside the band allocated to the radio astronomy service. Protection for observations conducted in this portion of the band may not be practicable.

NOTE 1 – A more extended list of astrophysically important and often observed line frequencies is available at <https://splatalogue.online/#/home>. The splatalogue database for astronomical spectroscopy is maintained by a wide collaboration of astronomers and atomic and molecular spectroscopists.

TABLE 2

**Radio frequency lines of the greatest importance to radio astronomy at frequencies between 275 and 1 000 GHz (not allocated in the RR)**

Substance	Rest frequency (GHz)	Suggested minimum band (GHz)	Notes <sup>(1)</sup>
Diazenylium (N <sub>2</sub> H <sup>+</sup> )	279.511	279.23-279.79	
Carbon monosulphide (CS)	293.912	292.93-294.21	
Hydronium (H <sub>3</sub> O <sup>+</sup> )	307.192	306.88-307.50	
Deuterated water vapour (HDO)	313.750	313.44-314.06	
Carbon monoxide (C <sup>18</sup> O)	329.330	329.00-329.66	
Carbon monoxide ( <sup>13</sup> CO)	330.587	330.25-330.92	
Carbon monosulphide (CS)	342.883	342.54-343.23	
Carbon monoxide (CO)	345.796	345.45-346.14	
Hydrogen cyanide (HCN)	354.484	354.13-354.84	
Formylium (HCO <sup>+</sup> )	356.734	356.37-357.09	
Molecular oxygen (O <sub>2</sub> )	368.498	368.13-368.87	
Diazenylium (N <sub>2</sub> H <sup>+</sup> )	372.672	372.30-373.05	(2)
Water vapour (H <sub>2</sub> O)	380.197	379.81-380.58	(2)
Hydronium (H <sub>3</sub> O <sup>+</sup> )	388.459	388.07-388.85	
Carbon monosulphide (CS)	391.847	390.54-392.24	
Molecular oxygen (O <sub>2</sub> )	424.763	424.34-425.19	
Carbon monoxide (C <sup>18</sup> O)	439.088	438.64-439.53	
Carbon monoxide ( <sup>13</sup> CO)	440.765	440.32-441.21	
Carbon monoxide (CO)	461.041	460.57-461.51	
Deuterated water vapour (HDO)	464.925	464.46-465.39	
Atomic carbon (C I)	492.162	491.66-492.66	
Deuterated water vapour (HDO)	509.292	508.78-509.80	
Hydrogen cyanide (HCN)	531.716	529.94-532.25	(2)
Carbon monosulphide (CS)	538.689	536.89-539.23	(2)
Water vapour (H <sub>2</sub> <sup>18</sup> O)	547.676	547.13-548.22	(2)
Carbon monoxide ( <sup>13</sup> CO)	550.926	549.09-551.48	(2)
Water vapour (H <sub>2</sub> O)	556.936	556.37-557.50	(2)
Ammonia ( <sup>15</sup> NH <sub>3</sub> )	572.113	571.54-572.69	(2)
Ammonia (NH <sub>3</sub> )	572.498	571.92-573.07	(2)
Carbon monoxide (CO)	576.268	574.35-576.84	(2)
Carbon monosulphide (CS)	587.616	587.03-588.20	(2)
Deuterated water vapour (HDO)	599.927	599.33-600.53	(2)
Water vapour (H <sub>2</sub> O)	620.700	620.08-621.32	(2)
Hydrogen chloride (HCl)	625.040	624.27-625.67	
Hydrogen chloride (HCl)	625.980	625.35-626.61	
Carbon monosulphide (CS)	636.532	634.41-637.17	

TABLE 2 (*end*)

Substance	Rest frequency (GHz)	Suggested minimum band (GHz)	Notes <sup>(1)</sup>
Carbon monoxide ( <sup>13</sup> CO)	661.067	658.86-661.73	
Carbon monoxide (CO)	691.473	690.78-692.17	
Molecular oxygen (O <sub>2</sub> )	715.393	714.68-716.11	(2)
Carbon monosulphide (CS)	734.324	733.59-735.06	(2)
Water vapour (H <sub>2</sub> O)	752.033	751.28-752.79	(2)
Molecular oxygen (O <sub>2</sub> )	773.840	773.07-784.61	(2)
Hydrogen cyanide (HCN)	797.433	796.64-798.23	
Formylium (HCO <sup>+</sup> )	802.653	801.85-803.85	
Carbon monoxide (CO)	806.652	805.85-807.46	
Atomic carbon (C I)	809.350	808.54-810.16	
Carbon monosulphide (CS)	832.057	829.28-832.89	
Molecular oxygen (O <sub>2</sub> )	834.146	833.31-834.98	
Carbon monosulphide (CS)	880.899	877.96-881.78	
Water vapour (H <sub>2</sub> O)	916.172	915.26-917.09	(2)
Carbon monoxide (CO)	921.800	918.72-922.72	(2)
Carbon monosulphide (CS)	929.723	926.62-930.65	
Water vapour (H <sub>2</sub> O)	970.315	969.34-971.29	(2)
Carbon monosulphide (CS)	978.529	977.55-979.51	(2)
Water vapour (H <sub>2</sub> O)	987.927	986.94-988.92	(2)

<sup>(1)</sup> The band limits are the Doppler-shifted frequencies corresponding to radial velocities of  $\pm 300$  km/s (consistent with line radiation occurring in the Milky Way Galaxy).

<sup>(2)</sup> These lines are observable only outside the Earth's atmosphere by, for example, using receivers located on high altitude balloons, aircraft, satellites, or other non-terrestrial platforms (see also RR Article 22, Section V).

TABLE 3

**Frequency bands allocated, or identified in RR No. 5.565, to the radio astronomy service that are preferred for continuum observations**

Frequency band (MHz)	Frequency band (GHz)
13.360-13.410	10.6-10.7
25.550-25.670	15.35-15.4
37.5-38.25 <sup>(1)</sup>	22.21-22.50
73-74.6 <sup>(2)</sup>	23.6-24.0
150.05-153 <sup>(3)</sup>	31.3-31.8
322-328.6	42.5-43.5
406.1-410	76-116 <sup>(1)</sup>
608-614 <sup>(4)</sup>	123-158.5 <sup>(1)</sup>
1 400-1 427	164-167
1 660-1 670	200-231.5
2 655-2 700 <sup>(1)</sup>	241-510 <sup>(1), (5)</sup>
4 800-5 000 <sup>(1)</sup>	602-720 <sup>(6)</sup>
	787-950 <sup>(7)</sup>

<sup>(1)</sup> These bands include secondary allocations.

<sup>(2)</sup> Allocation (primary) in Region 2, protection recommended in Regions 1 and 3.

<sup>(3)</sup> Allocation (primary) in Region 1, Australia and India.

<sup>(4)</sup> Allocation (primary) in Region 2, the African Broadcasting Area (606-614 MHz), China (606-614 MHz) and India. In Region 1 (except the African Broadcasting Area) and in Region 3 this band is allocated to RAS on a secondary basis.

<sup>(5)</sup> RR No. **5.565** identifies the frequency ranges 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, and 453-510 GHz for use by administrations for radio astronomy service, and frequency ranges 323-327 GHz, 371-388 GHz, 424-426 GHz, and 442-453 GHz for other passive services.

<sup>(6)</sup> RR No. **5.565** identifies the frequency range 623-711 GHz for use by administrations for radio astronomy service, and frequency ranges 611-630 GHz and 713-718 GHz for other passive services.

<sup>(7)</sup> RR No. **5.565** identifies the frequency ranges 795-909 GHz and 926-945 GHz for use by administrations for radio astronomy service, and frequency range 909-926 GHz for other passive services.

TABLE 4

**Frequency bands associated with redshifted neutral hydrogen**

Substance	Rest frequency	Redshift range <sup>(1)</sup>	Frequency range	Notes
Hydrogen (H I)	1 420.406 MHz	$20.9 > z > 6$	65.0-200.0 MHz	(2)
		$2 > z > 1$	473.0-710.0 MHz	(3)
		$0.48 > z > 0.22$	960.0-1 164.0 MHz	(4),
		$0.093 > z > 0$	1 300.0-1 427.0 MHz	(5)

<sup>(1)</sup> The parameter  $z [(f_{\text{emit}} - f_{\text{obs}})/f_{\text{obs}}]$  is known as the redshift. See Fig. 3.

<sup>(2)</sup> Portions of this frequency band are allocated on a primary basis in Region 2 (73-74.6 MHz) and on a primary basis in Region 1 (150.05-153.0 MHz) and identified in RR No. **5.149** in Regions 1 (73-74.6 MHz and 150.05-153 MHz) and Region 3 (73-74.6 MHz). Some national regulations indicate that no stations shall be authorized to transmit in the 73-74.6 MHz band. H I at redshifts of the physically important Epoch of Reionisation ( $6.0 < z < 20$ ) is expected to be observed in a frequency range of 65.0-200.0 MHz. See Fig. 3, left panel.

<sup>(3)</sup> Parts of this frequency range have a primary allocation in Region 2 (608-614 MHz), the African Broadcasting Area (606-614 MHz, RR No. **5.304**), China (606-614 MHz, RR No. **5.305**) and India (608-614 MHz, RR No. **5.307**). In Region 1 (except the African Broadcasting Area) and in Region 3 part of this band is allocated on a secondary basis (608-614 MHz, RR No. **5.306**). The frequency band 608-614 MHz is listed in RR No. **5.149** in Regions 1 and 3. Some national regulations indicate that no stations shall be authorized to transmit in the 608-614 MHz band, except for medical telemetry equipment. This frequency range corresponds to a redshift range within which the peak star formation activity takes place ( $1 < z < 2$ ). See Fig. 3, middle panel.

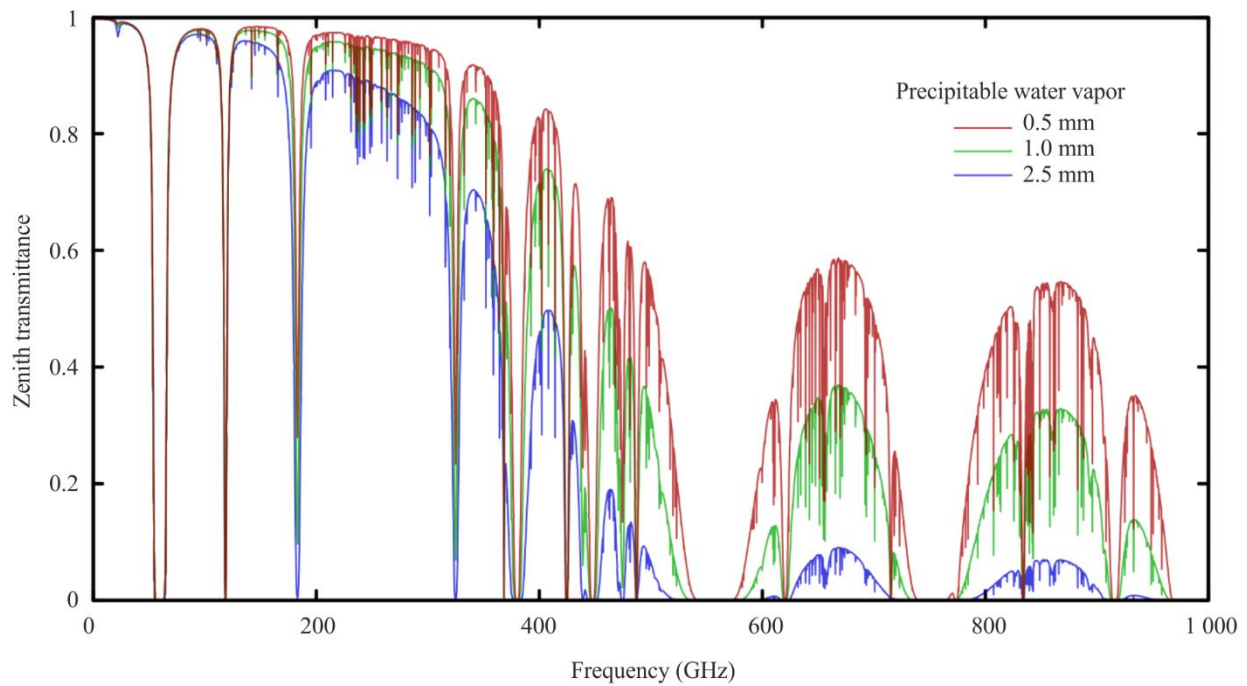
<sup>(4)</sup> No current international allocation for radio astronomy can be found in the Radio Regulations in this frequency band. This frequency range corresponds to a redshift range within which neutral hydrogen can still be observed directly in emission in galaxies, within which cosmic evolution is already observable (roughly  $0.5 > z > 0.2$ ). See Fig. 3, middle panel.

<sup>(5)</sup> Part of this frequency band is noted in RR No. **5.149** (1 330-1 400 MHz) and part of this frequency band is allocated to RAS on a primary basis and is also noted in RR No. **5.340** (1 400-1 427 MHz). An extension to lower frequencies is required to allow for Doppler shifts for H I observed in distant galaxies; the higher frequency limit accounts for blue-shifts of galaxies within the local volume. See Fig. 3, middle panel.

**Annex 1**

The preferred frequency bands for radio astronomy observations are dictated by natural processes, as illustrated in the following Figures.

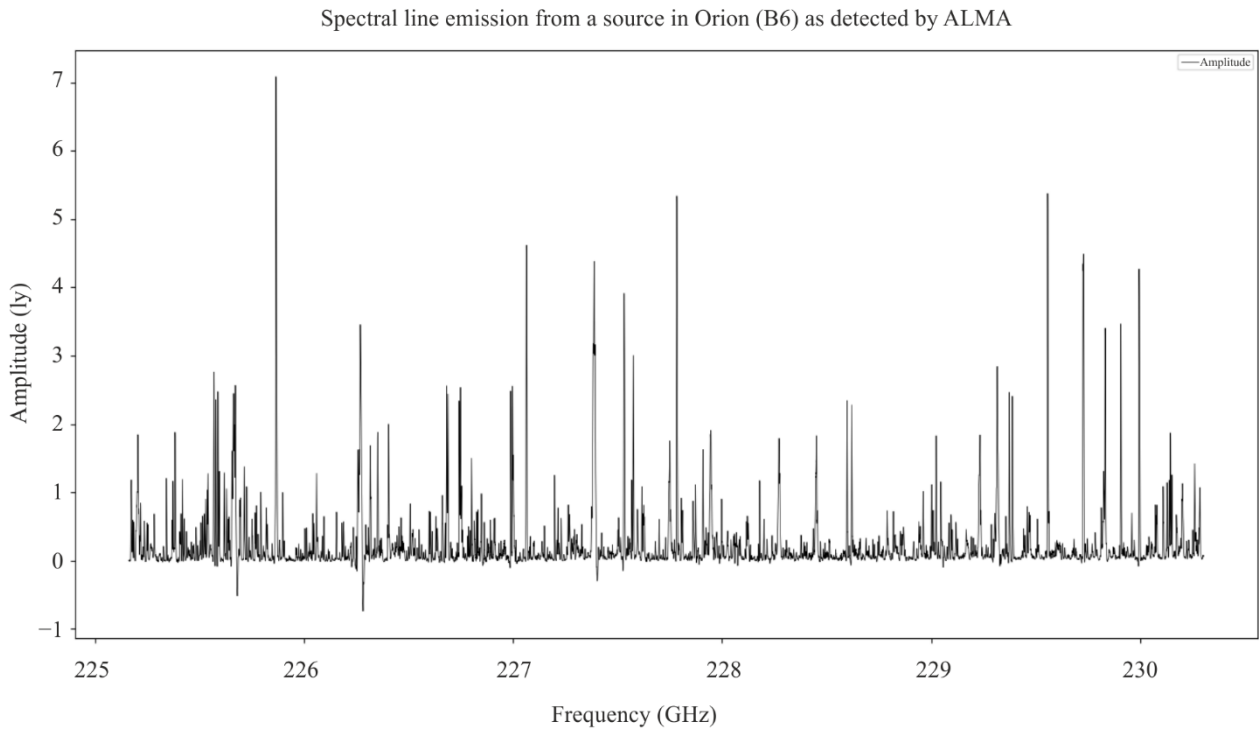
FIGURE 1  
Atmospheric transmission as a function of frequency



RA.0314-01

The spectral regions of high transparency are referred to as “atmospheric windows” and coincide with preferred frequency bands for Earth-based radio astronomy observations. The spectral transmittance curves shown here correspond to different values of precipitable water vapour (PWV) at a high, dry site. The three PWV values here correspond approximately to the annual quartiles at the site of the Atacama Large Millimeter/submillimeter Array.

FIGURE 2

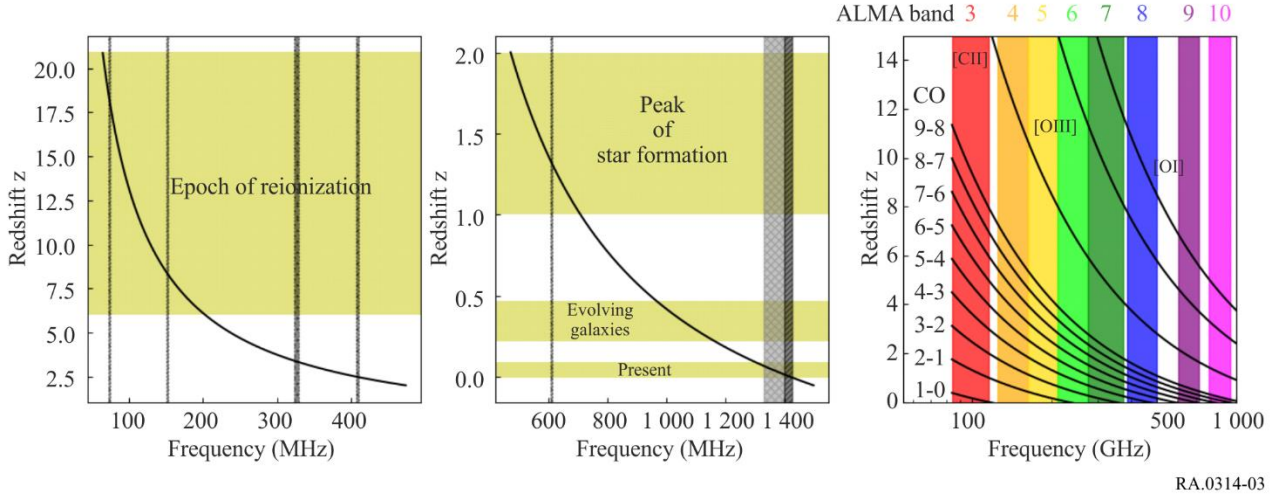
**Emission line spectrum illustrating the wealth of spectral lines detected in cosmic sources**

RA.0314-02

Radio astronomy observations reveal a wealth of spectral lines detected with a single observation over wide bandwidths. The intensity of each line is a function of the physical conditions of the astronomical source, including temperature and density. The spectral lines listed in Tables 1 and 2 include some of the strongest lines and some of the most astronomically interesting transitions detected from cosmic sources, but many other spectral transitions provide important information for astronomical research. Figure 2 shows a small portion of a spectrum from a source in the Orion molecular cloud in a portion of ALMA Band 6 (211-275 GHz). There is signal in nearly every channel. Each line corresponds to a molecular or atomic transition. Thousands of lines have already been observed in entire frequency region between about 10 MHz and 1 THz and above. The vertical axis is a measure of the flux-density per beam, where a jansky (Jy) is  $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ .

FIGURE 3

The expansion of the universe results in an apparent Doppler shift of spectral lines for distant sources

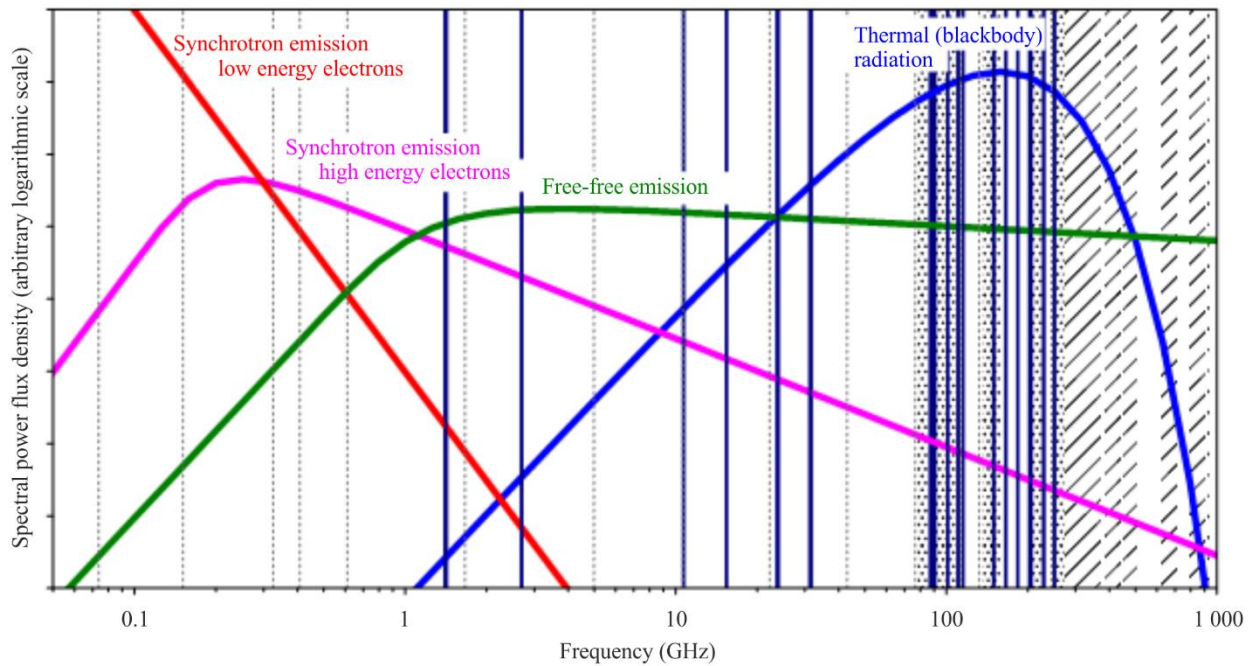


The parameter  $z$  represents the redshift and is calculated by  $(f_{\text{emit}} - f_{\text{obs}})/f_{\text{obs}}$ .

The left and middle panels of Fig. 3 illustrate redshifted frequencies of the neutral atomic hydrogen H I line. Yellow boxes highlight redshift ranges especially relevant for astronomical research (Table 4). Grey dotted ranges denote frequency bands in which RAS has a co-primary allocation in at least one Region, checked ranges denote noting in RR No. **5.149** only, hatched regions denote primary allocation and noting in RR No. **5.340**. All frequencies in the left and middle panels are currently observable by radio telescopes and they will be observed in their entirety by the Square Kilometre Array, one of the largest radio telescopes built in the near future. The right panel of Fig. 3 illustrates the redshifted frequencies for selected CO rotational transitions and [CII], [OIII], and [OI] fine structure lines (note that the square brackets denote a forbidden line) listed in Tables 1 and 2 above and in Recommendation ITU-R RA.1860. The colour-shaded vertical regions indicate the frequency range of the Atacama Large Millimetre/submillimetre Array receivers (bands). Observations of multiple CO lines from the same source enable the study of the physical conditions (temperature and density) associated with the molecular clouds and star forming regions in both nearby and extremely distant objects.

FIGURE 4

Spectral energy distributions of the strongest known cosmic sources



RA.0314-04

Radio astronomy observations at multiple frequencies are required to define the continuum spectrum of stars, galaxies, quasars, pulsars, and other cosmic radio sources. As illustrated in Fig. 4, the frequency bands specified in Table 3 are spaced at approximately one-octave separation in order to sample the spectral energy distribution of cosmic sources. Frequency bands allocated to the radio astronomy service on a co-primary basis for continuum observations are denoted by dotted lines in Fig. 4. Frequency bands also identified in RR No. **5.340** are denoted by solid lines. Frequency bands above 275 GHz identified for radio astronomy in RR No. **5.565** are denoted by hatched areas; these regions are appropriate for both continuum and spectral line observations. Linewidths in Fig. 4 are broader than the frequency allocations in many instances. Less than 1.7% of the radio spectrum below 11 GHz is allocated to the radio astronomy service on a co-primary basis and only 0.52% below 11 GHz is designated as ‘all emissions prohibited’ in RR No. **5.340**.

Representative spectral power flux-density distributions of pulsars (synchrotron emission of low energy electrons), supernova remnants (synchrotron emission of high energy electrons), ionized gas (free-free emission), and thermal sources (blackbody radiation) are illustrated in Fig. 4. Since the observed flux-density of an astronomical object is the combination of its intrinsic luminosity and distance to the source, the y-axis of Fig. 4 is on a relative logarithmic scale. The spectrum from one astronomical source can also be a linear combination of the displayed spectra, with contributions of variable strength from the different radiation processes. Measuring the shape of the observed spectrum then allows astronomers to derive relevant physical parameters of the object. The spectral power flux-density distributions shown in Fig. 4 span four orders of magnitude, for example from  $-290$  to  $-250$  dB(W m<sup>-2</sup> Hz<sup>-1</sup>). The exquisite sensitivity of radio astronomy receivers enables detection of very faint astronomical objects, at microjansky levels, where 1 jansky (Jy) is  $10^{-26}$  W m<sup>-2</sup> Hz<sup>-1</sup>.