Radio sources: useful data for EME equipment evaluation and optimization

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Foreword

The flux density, or flux, is given in Jansky (Jy), as well as in dB ($W/m^2/Hz$) or dB (J/m^2).
1 Jansky = 10^{-26} W/m²/Hz, or in logarithmic format, $0\,dB(Jy) = -260\,dB(W/m^2/Hz)$.
1 *Watt per square meter per hertz* (W/m²/Hz) is equivalent to 1 *Joule per square meter* (J/m^2). Both units are used here.

Flux data of radio sources are taken from [1] and [2]. Map of the radio sky is extracted from [3]. Equatorial coordinates (J2000.0), as well as other useful complementary information are published in [4]. Pictures are taken from Wikipedia.

The radio sources are classified in order of increasing right ascension.

Tycho Brahé's supernova

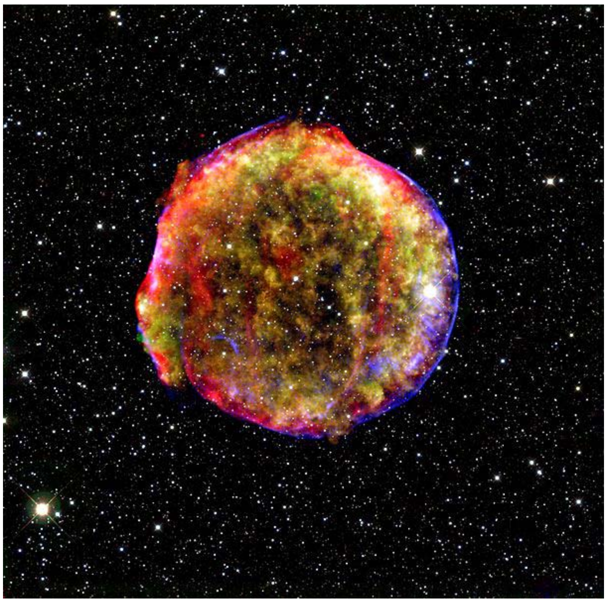
This radio source, listed as 3C10*, and sometimes referred to as Cassiopeia B, is related to the remnants of a supernova observed for the first time on November 11th, 1572, by the famous Danish astronomer Tycho Brahe (1546–1601). It was then brighter than Venus, but after March 1574, was no longer visible to the naked eye. Distance: ~7500 light–years. Radio spectrum can be found in [4]. The formula for the flux was derived from this spectrum by the author. Coordinates are available in Wikipedia.

Equatorial coordinates (J2000.0): $\alpha = 0^h25^m08.07^s$ $\delta = +64°09'55.7"$

Flux, between 100 MHz and 10000 MHz
$\log S = 3.461 - 0.585 \log F$ *S* in Jansky (Jy). *F* in MHz
$S_{dB} = -225.39 - 5.85 \log F$ *S* in dB(W/m²/Hz). *F* in MHz:

The table below shows the flux values for the VHF and above amateur bands. Note that these values are very low, close to the limit of the receiving capability of amateur equipment, mainly because of the relatively "reduced" sizes of the antennas.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	157.9	–238.0
432	83.1	–240.8
1296	43.7	–243.6
2320	31.1	–245.1
3400	24.8	–246.1
5760	18.2	–247.4
10368	12.9	–248.9



Tycho Brahé's supernova remnant as observed by the Chandra Space Telescope.

Taurus A

This radio source is linked to the famous Crab Nebula (also listed as Messier 1, M 1, NGC 1952 or 3C 144*), remnants of a supernova first observed by Chinese astronomers in July 1054 AD. The rotation period of the pulsar located at the center of the nebula amounts to 33 ms, or 30 revolutions per second, or 1800 rpm. Distance: ~ 6500 light–years. Radio data from [1].

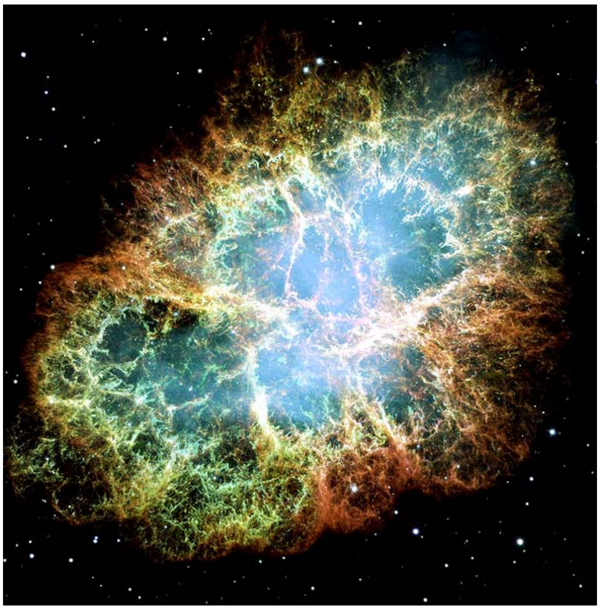
Equatorial coordinates (J2000.0) [4]: $\alpha = 5^h34^m32.0^s$ $\delta = +22°00'52.06''$

Flux, between 1000 MHz and 35000 MHz
$\log S = 3.915 - 0.299 \log F$ S in Jansky (Jy). F in MHz
$S_{dB} = -220.85 - 2.99 \log F$ S in dB(W/m²/Hz). F in MHz:

In the validity range of the formula, the accuracy of the given value in dB is about ± 0.4 dB, or approximately ± 4% for the same value given in Jy. Below 1000 MHz, the formula is still valid, but the accuracy is not guaranteed.

The table below shows the flux values for the VHF and above amateur bands.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	1860.6	–227.3
432	1339.6	–228.7
1296	964.6	–230.2
2320	810.4	–230.9
3400	722.9	–231.4
5760	617.5	–232.1
10368	518.0	–232.9
24048	402.8	–233.9



Taurus A, or Crab nebula, remnant of the supernova observed in 1054 AD by chinese astronomers.

See paper about measurements made on Taurus A at 435 MHz with amateur equipment, by Christian Monstein HB9SCT (German language).

http://www.monstein.de/astronomypublications/TaurusA/ORIONTAU.htm

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* 3C: *Third Cambridge Catalogue of Radio Sources*: published in 1959, it includes all sources detected and observed by the Cambridge Observatory on 159 and 178 MHz, since the beginning of radio astronomy until the date of its publication. The radio sources are listed in order of increasing right ascension, under the name 3C xxx, where xxx is their respective numbers.

Orion nebula

This radio source, also listed as M 42, NGC 1952 or 3C 145, is located south of Orion's belt. It is visible to the naked eye when the sky is clear and deep (without moon or "optical noise" of human origin). Distance: ~1340 light years. Radio data from [2].

Equatorial coordinates (J2000.0) [4]: $\alpha = 5^{h}35^{m}16.48^{s}$ $\delta = -5°23'22.84''$

Flux, between 1000 MHz and 10000 MHz
$\log S = 3.317 - 0.204 \log F$ *S* in Jansky (Jy), *F* in MHz
$S_{\mathrm{dB}} = -226.83 - 2.04 \log F$ *S* in dB(W/m²/Hz), *F* in MHz:

The table below shows the flux values for the VHF and above amateur bands.

Values below 1000 MHz, displayed in *italics*, are given without guarantee. Some publications write about an increasing flux rate up to 1000 MHz, with a maximum around 1000 MHz, and then decreasing, as observed with other radio sources.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	*752.8*	*–231.2*
432	*601.7*	*–232.2*
1296	480.9	–233.2
2320	427.0	–233.7
3400	394.7	–234.0
5760	354.7	–234.5
10368	314.6	–235.0

Orion nebula

On the radio–sources plot, at the end of this document, the part of the Orion nebula flux curve below 1 GHz is drawn in dotted line, spectral data below 1 GHz being uncertain.

Virgo A

This radio source, listed as 3C 274, is linked to the elliptical galaxy M 87, or NGC 4486, the main representative of the Virgo galaxy cluster. Radio data from [1].

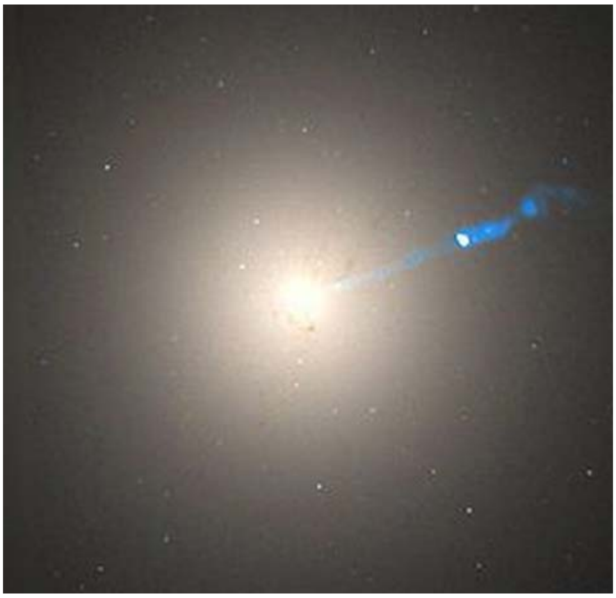
Equatorial coordinates (J2000.0) [4]: $\alpha = 12^h30^m48.7^s$ $\delta = +12°23'15''$

Flux, between 400 MHz and 25000 MHz
$\log S = 5.023 - 0.856 \log F$ S in Jansky (Jy), F in MHz
$S_{dB} = -209.77 - 8.56 \log F$ S in dB(W/m²/Hz), F in MHz:

In the validity range of the formula, the accuracy of the given value in dB is about ± 0.4 dB, or approximately ± 4% for the same value given in Jy. Below 1000 MHz, the formula is still valid, but the accuracy is not guaranteed.

The table below shows the flux values for the VHF and above amateur bands.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	1497.8	–228.2
432	584.8	–232.3
1296	228.4	–236.4
2320	138.7	–238.6
3400	99.9	–240.0
5760	63.7	–242.0
10368	38.5	–244.1
24048	18.7	–247.3



Virgo A

The blue line appearing on the right side of the picture is not a photographic artefact. This phenomenon is part of the galaxy. It could be a jet of material ejected at relativistic speeds by a supermassive black hole located at the center of the galaxy (for more details, see Wikipedia).

See paper about measurements made on Virgo A at 435 MHz with amateur equipment, by Christian Monstein HB9SCT (English language).

http://www.monstein.de/astronomypublications/VirgoA/virgo.pdf

Sagittarius A*, Sagittarius A East and Sagittarius A West

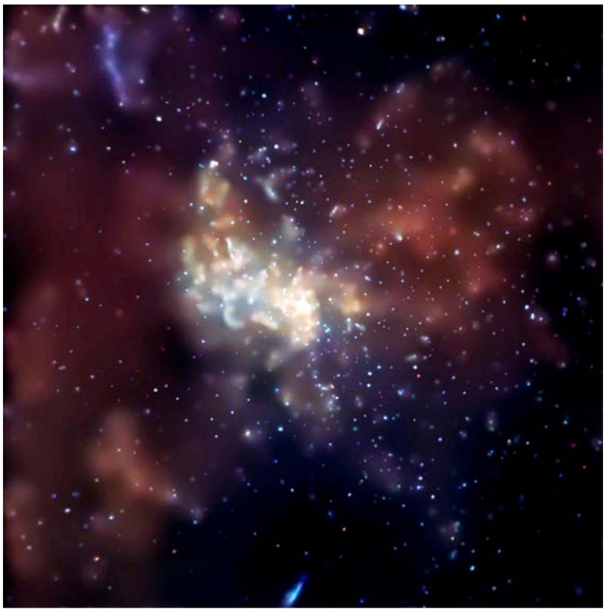
This mulitple radio source is located at the center of our Galaxy. Most astrophysicists assume that the center of the Galaxy is occupied by a supermassive black hole whose mass is estimated around 4.31 ± 0.38 million solar masses, about $8.52\ 10^{36}$ kg. If this estimation gets refined, Sagittarius A* is the most likely candidate for the title of "black hole" (the symbol * refers to objects of the black hole type). Sagittarius A* is a point source, but it is part of a system composed of three sources, the other two being *Sagittarius A East* and *Sagittarius A West*, which are both extended sources.

Estimated distance: 25900 ± 1400 light–years.

Equatorial coordinates of Sgr A* (J2000.0) [4]: $\alpha = 17^h45^m40.0409^s$ $\delta = -29°00'28.118''$

No data or formula for the flux as a function of frequency is presently available.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144		
432		
1296	No data available	
2320		
3400		
5760		
10368		
24048		



Sagittarius A* and its "mates"

Apart from the Sun, the Sagittarius group *(Sgr A*, Sgr A East* and *Sgr A Ouest)* is the most powerful radio source in the sky. It is easily observable with EME equipment, but for European latitudes, remains low on the horizon (maximum 22° for 39° north, does not rise for latitude higher than 61° north).

Omega nebula

This radio source, listed as M 17 or NGC 6618 is located within the Sagittarius constellation. Estimated distance: from 5000 to 6000 light–years. Radio data from [2].

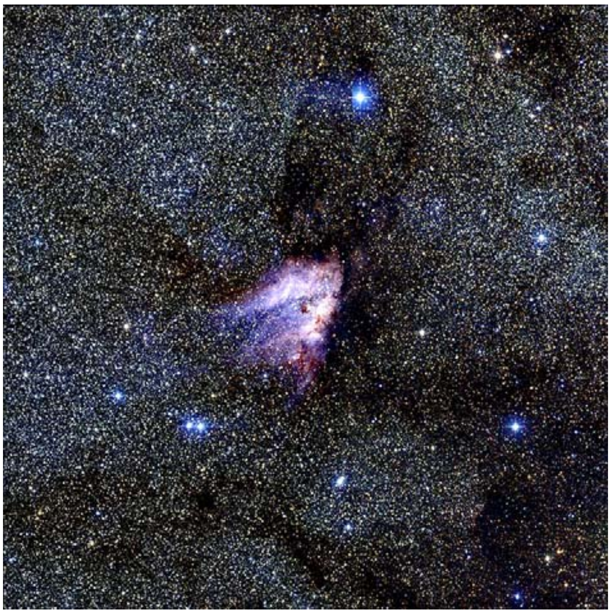
Equatorial coordinates (J2000.0) [4]: $\alpha = 18^h 20^m 47.1^s$ $\delta = -16°10'17''$

Flux, between 400 MHz and 25000 MHz
$\log S = 4.056 - 0.378 \log F$ S in Jansky (Jy), F in MHz
$S_{\text{dB}} = -219.44 - 3.78 \log F$ S in dB(W/m²/Hz), F in MHz:

No information is available regarding the accuracy of this formula.

The table below shows the flux values for the VHF and above amateur bands.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	1738.4	–227.6
432	1147.6	–229.4
1296	757.6	–231.2
2320	607.9	–232.2
3400	525.7	–232.8
5760	431.1	–233.7
10368	345.2	–234.6
24048	250.9	–236.0



Omega nebula

Cygnus A

Extragalactic radio source also listed as 3C 405. Its origin and distance are not yet clear (see *Comments* at the end of the document). Supposed distance: 550 to 800 million light–years (nice DX isn't it !). Radio Data provided by [1].

Equatorial coordinates (J2000.0) [4]: $\alpha = 19^h59^m28.36^s$ $\delta = +40°44'02"$

Flux, between 20 MHz and 2000 MHz	Flux, between 2000 MHz and 31000 MHz
$\log S = 4.695 + 0.085 \log F - 0.178 \log^2 F$ *S* in Jansky (Jy), *F* in MHz	$\log S = 7.161 - 1.244 \log F$ *S* in Jansky (Jy), *F* in MHz
$S_{\mathrm{dB}} = -213.05 + 0.85 \log F - 1.78 \log^2 F$ *S* in dB(W/m²/Hz), *F* in MHz:	$S_{\mathrm{dB}} = -188.39 - 12.44 \log F$ *S* in dB(W/m²/Hz), *F* in MHz:

Within the validity range of the first formula, the accuracy of the given value in dB is about ± 0.2 dB, or approximately ± 2% for the same value given in Jy.

Within the validity range of the second formula, the accuracy of the given value in dB is about ± 0.5 dB, or approximately ± 5% for the same value given in Jy.

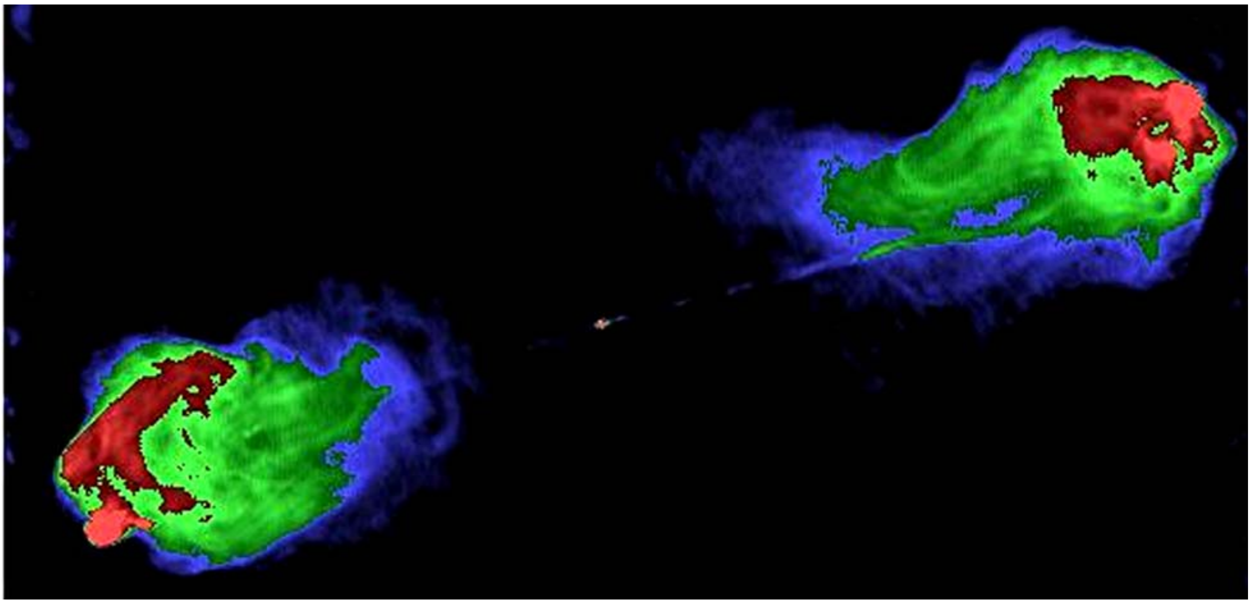
The table below gives the flux values for the VHF and above amateur bands.

Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)
144	11200.6	–219.5
432	4815.8	–223.2
1296	1718.1	–227.6
2320	898.5	–230.5
3400	535.9	–232.3
5760	280.8	–235.5
10368	132.4	–238.8
24048	51.4	–242.9

The polarization of Cygnus A signals is not purely randomly scattered, but rather shows some degree of ellipticity without being fully linear.

Estimated power of Cygnus A at 432 MHz.

Path attenuation ($550 \cdot 10^6$ light–years): ~ 520 dB.
Flux density at source level:
$S = -223 + 520 = +296$ dB(W/m²/Hz) !!!
If the radio source was located at the same distance as that of the Sun (150 million km), the flux density at Earth level would amount to + 48 dB(J/m²). Under such conditions, a receiver having a bandwidth of 2500 Hz connected to an antenna having an equivalent capture area of 1 m² would collect a power level of + 82 dBW or, expressed in units of power, about 165 MW !!



Cygnus A ["radio" image in false colours]

Cassiopeia A

This radio source, first discovered in 1947 and later listed as 3C 461, is related to the remnant of a supernova observed, either in 1667 or in 1680. Distance: ~11000 light–years. Radio data from [1].

Equatorial coordinates (J2000.0) [4]: $\alpha = 23^h 23^m 27.94^s$, $\delta = +58°48'42.4''$

Flux density formula between 300 MHz and 31000 MHz.

As the flux slightly decreases from year to year, the full formula is divided into two parts:

1) Frequency dependent part only:

$$A = 5.745 - 0.77 \log F \qquad (1)$$

2) Secular part, frequency and time dependent:

Epoch of origin: 1980.0

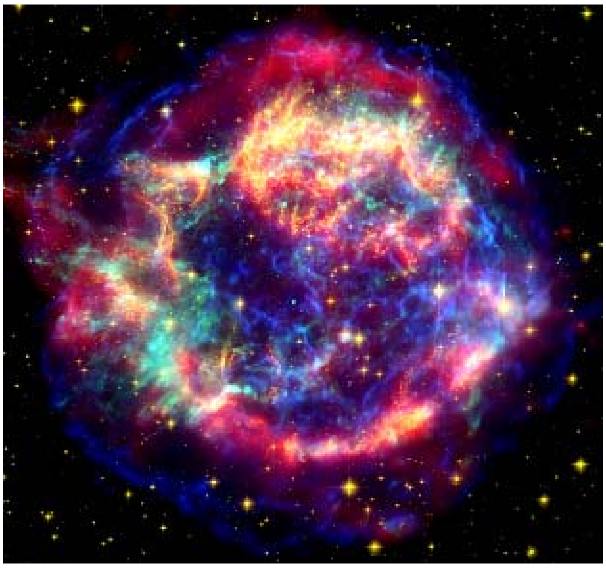
$$B = (0.0187 - 0.003 \log F)(y - 1980.0) \qquad (2)$$

where y is the current "decimal year" (example: 2014 May 31 = 2014.41).

The completed formula then reads:

$$\log S = A + \log(1 - B) \qquad (3)$$

With S in Jansky (Jy) and F in MHz.



Cassiopeia A remnant

Within the validity range of the completed formula, the accuracy of the given value in dB is about ± 0.4 dB, or approximately ± 4% for the same value given in Jy.

The table below gives the flux values for the VHF and above amateur bands.

	1980.0		2014.5	
Band (MHz)	Jansky (Jy)	dB(W/m²/Hz)	Jansky (Jy)	dB(W/m²/Hz)
144	12107.7	–219.2	7001.2	–221.5
432	5196.1	–222.8	3261.2	–224.9
1296	2229.9	–226.5	1509.7	–228.2
2320	1424.2	–228.5	1001.5	–230.0
3400	1061.1	–229.7	764.4	–231.2
5760	707.1	–231.5	526.1	–232.8
10368	449.7	–233.5	346.5	–234.6
24048	235.3	–236.3	190.2	–237.2

Over the past 34 years (since 1980), the flux decreased by about 2.3 dB in the lower part of the spectrum, and only 0.9 dB in its upper part.

Moon

The radiation of the Moon in the hertzian part of the spectrum can be compared to that of a black body in the same part. Radio flux density is then given by the Rayleigh–Jeans formula:

$$S = \frac{2\mathrm{k}T\Omega}{\lambda^2} \tag{4}$$

which can also be written as follows:

$$S = \frac{2\mathrm{k}T\Omega F^2}{\mathrm{c}^2} \tag{5}$$

Where:

S : Flux density, in Joules per square meter (J/m^2), or in Jansky (Jy): 1 Jy = 10^{-26} J/m^2.
k : Boltzmann's constant: k = $1.3806505 \cdot 10^{-23}$ J/°K
T : Black body température, in degrees Kelvin (°K)
Ω : Solid angle of the source as seen by the observer (steradian).
λ : Wavelength, in meters (m).
F : Frequency, in Hertz (Hz).
c : Speed of light, in meters per second (m/s): c = $2.997\,924\,58 \cdot 10^8$ m/s

Moon solid angle is given by the following geometrical formula:

$$\Omega = \frac{\pi\,\mathrm{r}^2}{d^2} \tag{6}$$

Where:

r : Moon's radius, in meters: r = 1 737 965.5 m
d : Observer to Moon distance, in meters.

The following formula can then be derived from (5) and (6):

$$\boxed{S = \frac{2\pi\,\mathrm{k}T\,\mathrm{r}^2 F^2}{d^2\mathrm{c}^2}} \tag{7}$$

If S is expressed in Jy, formula (4) then reads:

$$\boxed{S_{\mathrm{Jy}} = \frac{2\pi\,\mathrm{k}T\,\mathrm{r}^2 F^2}{d^2\mathrm{c}^2}10^{26}} \tag{8}$$

Calculations are usually carried out under logarithmic format.

After replacement of the constants by their respective numerical values in (7) and (8), these equations then read, still with d in km, T in °K and F in MHz:

$$\log S = -20.5353 - 2\log D + 2\log F \tag{9}$$

$$\log S_{\mathrm{Jy}} = 5.4647 - 2\log d + \log T + 2\log F \tag{10}$$

If the average value of 384 400 km is taken for d, equations (9) and (10) then read:

$$\log S = -31.7049 + \log T + 2\log F \tag{11}$$

$$\log S_{\mathrm{Jy}} = -5.7049 + \log T + 2\log F \tag{12}$$

If the average value of 200°K is taken for T, equations (9) and (10) then read:

$$\log S = -29.4038 + 2\log F \tag{13}$$

$$\log S_{\mathrm{Jy}} = -3.4038 + 2\log F \tag{14}$$

Finally, if the flux is expressed in dB(J/m^2), the reference being set at 1 J/m^2 while retaining the values of T and d as set forth above, we obtain the following practical formula:

$$\boxed{S_{\mathrm{dB}} = -294.038 + 20\log F} \tag{15}$$

The following table gives the lunar flux values in the amateur bands, as well as in the TVRO Ku band.

Reminder: 1 J/m^2 = 1 W/m^2/Hz

Band (MHz)	Jansky (Jy)	dB(J/m²)
144	8.2	–250.9
432	73.6	–241.3
1296	662.8	–231.8
2320	2123.9	–226.7
3400	4751.5	–223.2
5760	13092.2	–218.8
10368	42418.7	–213.7
TVRO 12 GHz	56823.8	–212.5
24048	228205.3	–206.4

The overall accuracy of the flux value in dB(J/m^2) or in Jy depends on the chosen formula. The table was compiled using formula (12). The Earth–Moon distance variation between perigee and apogee leads to a ripple of ± 0.6 dB on the signal amplitude. Temperature fluctuations between "Cold Moon" and "Hot Moon" are the cause of variations of about ± 2.7 dB.

Venus

Like for the Moon, Venus radiation in the hertzian part of the spectrum can be compared to that of a black body, and therefore, also obeys the Rayleigh–Jeans law.

However, this radiation is extremely low, and only amateur stations equipped with 10 GHz high–tech means (solid parabolic dishes of diameters at least 4.50 m and ultra low noise preamp) are likely to be able to detect this weak radiation.

In the case of Venus, the key parameter is its distance from the earth, which varies roughly from 42 million kilometers at the conjunction, up to 258 million kilometers at the opposition. At its maximum elongation (east or west, about 46°), it is 104 million kilometers from Earth. Its diameter is about 12100 km and its average temperature is about 600°K

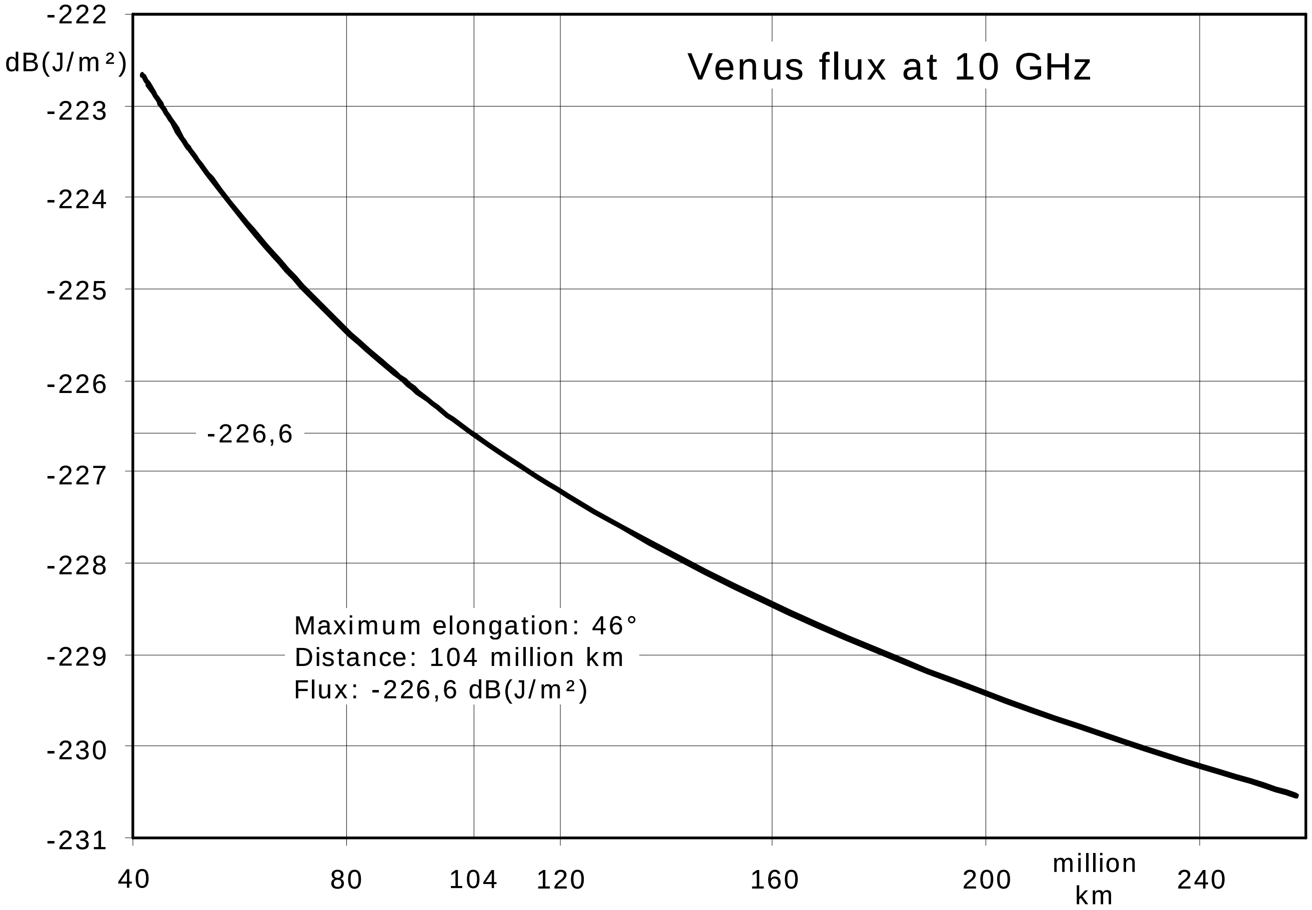
As for the Moon, and after replacement of constants by their numerical values in equation (4), the flux formula then reads, with $T = 600$°K, $F = 10368$ MHz, r = 6052 km, and d in million kilometers:

$$\log S = -20.6416 - 2\log d \tag{16}$$

$$\log S_{\mathrm{Jy}} = 5.3584 - 2\log d \tag{17}$$

Finally, if the flux is expressed in dB (J/m^2), the reference being set at 1 J/m^2 while retaining the values of T and F as set forth above, the practical formula then reads:

$$\boxed{S_{\mathrm{dB}} = -206.416 - 20\log d} \tag{18}$$



Note: The above plot shows the flux [dB(J/m^2)] as a function of the distance [10^6 km], and not as a function of the distance logarithm as expressed by equation (15).

Hypothetical example

Observation frequence: 10368 MHz
Observed radio–source:
Venus at its maximum elongation: 46°
Distance ≈104 000 000 km
Flux ≈ 2200 Jy ≈ –226.6 dB(J/m^2)
"Cold sky" temperature: 5°K

Parameter	value	unit
Antenna* diametre	4.50	m
Antenna gain	51.7	dBi
Overall RX noise figure	0.69	dB
Overall RX noise temp.	50.0	°K
Antenna noise temperature	11.1	°K
***Y = (S+N)/N* Ratio**	**0.15**	**dB**
Factor of merit	33.8	dB/°K

Venus in true colours, as seen by Mariner 10

* The parabolic dish is supposed solid and optimized. Its gain is calculated according to its diameter.

Comments

Radiosources in general

Signal levels of radiosources are extremely weak, averaging around 0.1 to 1.5 dB above the receiver idling noise. However, these hundredths of yoctojoules/m^2 * can be detected at the IF output of the converter with, instead of the regular traffic receiver, a radiometer or an SDR.

In general, such levels can be "viewed" with a radiometer or an SDR, provided these devices operate in "integrator" mode, with an integration time of at least a few tens of seconds. However, the relative uncertainty remains important for levels lower than 0.5 dB. It can therefore be concluded from these measurements that, if the equipment is capable of receiving these very weak signals, it is impossible to properly evaluate them. It can only be said that they have been detected, which is already not too bad ! The signals from Tycho Brahé's supernova stand at these levels, just at the limit of what a well equipped EME station can detect. Note that Virgo A is in an area of cold sky, making it theoretically easily identifiable (see radio sky map below).

Moon

At 144 and 432 MHz, the Moon hertzian thermal radiation is unobservable with regular amateur EME equipment. On 1296 MHz, it can only be correctly detected with an "advanced" EME installation, in other words, a large antenna and a receiver with a very low noise front end optimized at best.

Then, the higher the frequency goes up, the more the flux increases, and even 12 GHz TVRO installations of consumer type with modest antenna sizes can detect the thermal radiation of the Moon, provided readout devices are added at the output of the demodulation box (from simple meter up to sophisticated post–detection circuits, data processing computer, SDR, etc.).

If the antenna gain is higher than 51 dBi, its half–power aperture solid angle becomes smaller than that of the Moon. As a result, Moon noise does not increase much, even though the antenna gain significantly increases. A so–called "extended source correction " should then be applied.

Venus

Venus thermal radiation is unobservable with amateur means below 10 GHz. Even on this frequency, it is still difficult to detect. The calculation shows that a 4.50 m solid dish should be a minimum. An antenna of same diameter, but built with mesh, even with tight pitch, may still pick up excessive ground noise through the mesh, which would mask the faint "whisper" received from Venus.

Controversies about the distance of Cygnus A

Once the optical redshift of Cygnus A has been demonstrated, it was deduced that its distance from the Earth might probably range between 550 and 800 million light–years. The question which then arose was to understand the mechanism through which such powerfull a radio source could be supplied, whereas the corresponding optical object was relatively modest. After many years of research, it seems that Cygnus A would rather be located in the galactic plane, like most other radio sources, and not aligned with it by perspective effect (see sky map below), as would suggest the first idea. One of the arguments in favor of the "short distance" hypothesis is that the galactic plane, a dense absorbing gas area, would be an effective "attenuator" for any optical radiation coming from beyond the Milky Way. Under these conditions Cygnus A would belong to our Galaxy, just like Taurus A and Cassiopeia A. To date, nothing is resolved and discussions are always in progress... For more details, see Wikipedia and links to specialized websites dealing with these problems.

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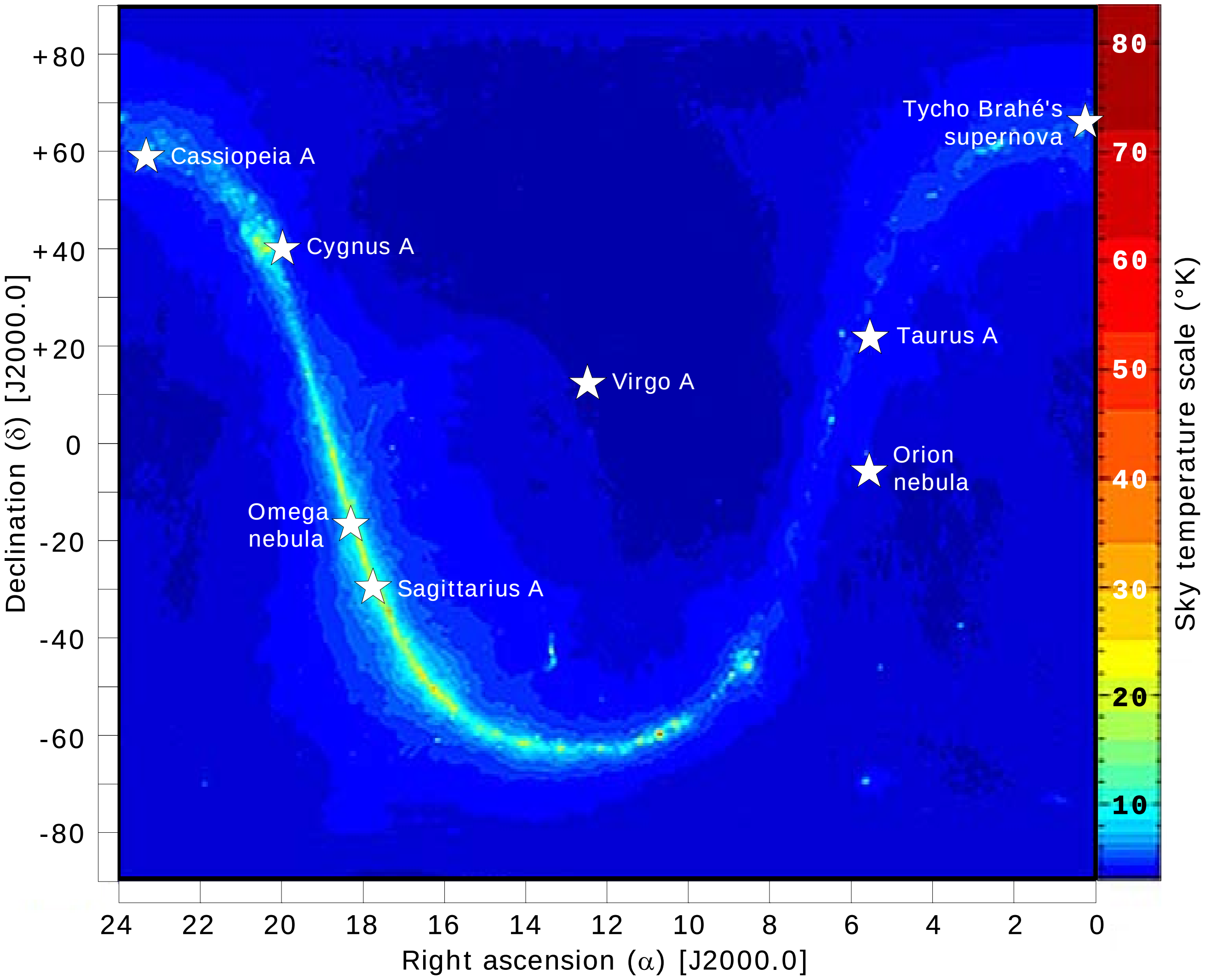
* prefix *yocto* = 10^{-24} example: 1 yW = 10^{-24} W

Radio sky map at 1413 MHz (Neutral hydrogen H1 line)

Radio sources are marked with a star. Apart from Cygnus A and Virgo A, other sources belong to our Galaxy and are positioned along the Milky Way. The various isolated and unmarked dots are either discrete radio sources, or "hot spots" of the Milky Way.

As Moon, Venus and Sun continuously move on the sky, they are not represented on this map.



References

[1] Baars J. W. M., Genzel R., Pauliny–Todt I. I. K. Witzel A.: (1977): *The Absolute Spectrum of Cas A; An Accurate Flux Density Scale and a Set of Secundary Calibrators*. Max Planck Institut für Radioastronomie, auf dem Hügel 69, D–53000 Bonn, BRD / FRG.

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[3] Dinnat E.P., Le Vine D.M., Abraham S. and Floury N.: (2009): *Map of Sky background brightness temperature at L–band.*

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Picture credits: Wikipedia

Moon and radio-sources