# Brightness in Radio Astronomy



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## General Terms

The brightness of celestial sources can be expressed in several different ways. The terms used by *astronomers* for these quantities include:

- **Energy** - the total radiative energy emitted by a source over some range of wavelengths (or frequencies) during some time interval, measured in joules, ergs, etc., e.g., the total photon energy yield of a typical supernova explosion is roughly $10^{44}$ joules (or $2 \times 10^{29}$ megatons of TNT!).

- **Luminosity or Intrinsic Brightness** - the energy emitted from a source in all directions per unit time, often measured in watts (joules per second), e.g, the luminosity of the Sun over all wavelengths is about $3.846 \times 10^{26}$ W. (Physicists use the term *power* to describe this quantity.)

- **Flux or Apparent Brightness** - power passing through a unit area, useful for measuring energy coming from a distant, relatively compact object, like the Sun. (Warning: physicists use the term *intensity* to describe this quantity, and *flux* to describe field strength summed over an area!)

  - **Specific Flux** - flux per unit wavelength or frequency, e.g., in watts per square meter per hertz [W $m^{-2}$ $Hz^{-1}$].

  - **Integrated Flux** - the sum of specific flux over a range of wavelengths or frequencies, e.g., in watts per square meter [W $m^{-2}$]. (Optical astronomers sometimes express the logarithm of integrated flux in units of *magnitudes*.)

- **Intensity or Surface Brightness** - flux passing through a unit solid angle, like a square degree or steradian, useful for measuring energy coming from part of an extended object, like part of our Galaxy. (Warning: physicists use the term *irradiance* to describe this quantity, and *intensity* to describe what astronomers call *flux*!)

  - **Specific Intensity** - intensity per unit wavelength or frequency, e.g., in watts per square meter per hertz per steradian [W $m^{-2}$ $Hz^{-1}$ $sr^{-1}$].

  - **Integrated Intensity** - the sum of specific intensity over a range of wavelengths or frequencies, e.g., in watts per square meter per steradian [W $m^{-2}$ $sr^{-1}$]. (Optical astronomers sometimes express the logarithm of integrated intensity in units of *magnitudes per square arcsecond*.)

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## Special Terms

*Radio* astronomers use some terms and units for a couple of the above quantities that may be unfamiliar even to optical astronomers!

- **Flux Density** is specific flux explicitly in per-frequency terms and is measured in **janskys**. These units are named for Karl Jansky, who first detected extraterrestrial radio emission in the 1930s, and are defined as: 1 Jy = $10^{-26}$ W $m^{-2}$ $Hz^{-1}$.

- **Brightness Temperature** is a proxy for specific intensity and is measured in **kelvins**, which are like degrees Celsius but are counted up from absolute zero (0.00 K = -273.15°C = -459.67°F). The brightness temperature is the temperature needed for a blackbody (thermal) radiator to produce the same specific intensity as the observed source. This does *not* mean that the radiation from any given source *is* from a blackbody -- in fact a lot of radio emission is from *non-thermal* mechanisms (like synchrotron; see below) -- but it is equal to the physical temperature for purely thermal sources (e.g., the cosmic microwave background radiation), and it is directly proportional to the specific intensity in the low-frequency limit (certainly for frequencies under 10 GHz, and often the limit is higher):

  $I_\nu = 2\,\nu^2\,k\,T_b\,/\,c^2$ $\quad$ ($h\,\nu \;\; << \;\; k\,T$ , so typical photon energy is much less than typical thermal energy per particle),

  where $I_\nu$ = specific intensity [W $m^{-2}$ $Hz^{-1}$ $sr^{-1}$] ,
  $T_b$ = brightness temperature [K] ,
  $T$ = physical temperature [K] ,
  $\nu$ = frequency [Hz] ,
  $c$ = the speed of light = $2.998 \times 10^8$ m $s^{-1}$ ,
  $k$ = Boltzmann's constant = $1.381 \times 10^{-23}$ J $K^{-1}$ ,
  and $h$ = Planck's constant = $6.626 \times 10^{-34}$ J s .

- **Conversion:** If the specific intensity of a source $I_\nu$ is constant within the "beam", or the solid angle Ω *in steradians* over which a radio telescope is sensitive, then its flux density $S_\nu$ is related to intensity as $S_\nu = I_\nu\,\Omega$, and its flux density and brightness temperature are related in turn by

  $S_\nu = 2\,\nu^2\,k\,T_b\,\Omega\,/\,c^2$ $\quad$ ($h\,\nu \;\; << \;\; k\,T$) ,

  where the effective solid angle of an elliptical Gaussian beam is

  $\Omega = \pi\,\theta_A\,\theta_B\,/\,[4\ln(2)]$ ,

  and $\theta_A$ and $\theta_B$ are the *full widths at half power* of the beam's major and minor axes *in radians*.

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# How Much is a Jansky?

Celestial sources of radio emission are much fainter than most human sources of radio waves, whether intentional (broadcast stations, cell phones) or otherwise (power lines, microprocessors, etc.). It is for this reason that radio astronomers seek observing sites far from population centers: to minimize potential interfering signals, just as optical astronomers seek to avoid "light pollution". To understand just how faint natural radio sources are, and what a jansky really measures, it is useful to make a quantitative comparison with more familiar "anthropogenic" radio signals.

FM radio broadcast stations in the United States typically have 100 kilowatts of effective radiated power (ERP), which includes gain factors from the transmitting antenna design (most radiation goes out horizontally but is equally distributed in azimuth, with a gain of typically 5 to 10 times that of an isotropic radiator, so the actual equivalent isotropic radiated power is only 10-20 kW). Such stations have a usual range of 50 miles = 80 km. The broadcast power will be reduced by some form of inverse-square law, even though it isn't isotropic. For simplicity, let's ignore any propagation effects and assume the arriving power density (APD) is given by an isotropic pattern modified by the gain, with the receiver in the direction of maximum gain. In this case,

$$\mathrm{APD} = \mathrm{ERP} / (4\,\pi\,d^2)$$

where $d$ = the distance from transmitter to receiver. The bandwidth (BW) allocated to 1 FM station is 200 kHz. Let's assume the signal strength is uniform across this bandwidth. For the above parameters, the flux density at a receiver 80 km from the station -- near the edge of its effective range -- in the optimal-gain path will be:

$$\begin{aligned} S_\nu &= \mathrm{APD} / \mathrm{BW} \\ &= \mathrm{ERP} / (4\,\pi\,d^2\ \mathrm{BW}) \\ &= 10^5\ \mathrm{W} / [4 \times 3.14 \times (8 \times 10^4\ \mathrm{m})^2 \times (2 \times 10^5\ \mathrm{Hz})] \\ &= 6.2 \times 10^{-12}\ \mathrm{W\ m^{-2}\ Hz^{-1}} \\ &= 6.2 \times 10^{14}\ \mathrm{Jy} \end{aligned}$$

where 1 Jy = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$ as noted above.

For comparison, most radio astronomy sources have signal strengths of a few Jy or less. The Sun, which is the brightest celestial source at most frequencies, has a flux density of about $10^6$ - $10^8$ Jy at 1 GHz, depending on whether there is surface activity (flares, etc.) or not. The brightest supernova remnant, Cassiopeia A, is about 3000 Jy at 1 GHz but a whopping 20,000 Jy at 100 MHz (the FM broadcast band), because it's a highly nonthermal (synchrotron) source -- as is Solar activity at these frequencies (Cas A is intrinsically much brighter than the Sun but appears fainter because it's a lot farther away). The faintest 1.4 GHz sources in recent large-scale radio surveys like the NRAO-VLA Sky Survey are a few milli-janskys. Newer, deeper surveys like the Evolutionary Map of the Universe project are targeting sources at the 50 µJy (50 micro-janskys) level, which is about 100 times fainter than the NVSS, or 60 *million* times fainter than Cas A. As you might surmise, such detections require that there is *no* significant interference from nearby radio broadcast stations!

It's also noteworthy that the brightness contrast between radio-frequency interference and radio astronomical sources is *much greater* than that between optical light pollution and most optical astronomical sources! Inner-city skies (when clear) can be up to 100 times (5 magnitudes) brighter than the darkest night skies far from any artificial light sources, reducing the number of visible stars from thousands to dozens. But as indicated above, a stray radio broadcast can easily be a *million* times brighter than the Sun at radio wavelengths, and a *trillion* times brighter than more "ordinary" radio sources! The contrast in the latter case is similar to that between the optical brightness of the Sun and the 3rd-magnitude stars that fill in many of the fainter parts of prominent constellations in the night sky.

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# How "Hot" is the Sky?

The Universe does not have a single physical temperature (if it did, then life could not exist, according to the laws of thermodynamics). Instead, it contains a mixture of hot and cold objects, running the gamut from a few kelvins to billions of kelvins. All things produce radiation of one sort or another over a range of frequencies, which can be characterized in flux, intensity, or brightness temperature terms.

At radio frequencies, the major types of radiation are:

- **Continuum radiation** from changes in speed or direction of free charged particles in space, primarily electrons, which includes:
  - **Thermal continuum** from free electrons curving past positive ions (*bremsstrahlung radiation*), as occurs in stars, planets, and interstellar clouds heated by starlight; this is characteristic of anything in some form of thermal equilibrium, including blackbodies
  - **Non-thermal continuum** from electrons moving in magnetic fields (*cyclotron emission*, which becomes *synchrotron emission* for relativistic motion), as occurs in pulsars, supernova remnants, and the cores of active galaxies
- **Spectral lines** from discrete changes in the quantum configurations of atoms or molecules, for example, the bound electron in a neutral hydrogen atom changing its quantum spin from the same direction as the proton's to the opposite direction, which has a slightly lower energy state, and emitting a 1.4 GHz (21 cm) photon. (Most spectral lines arise in "thermal" situations, but a few like *masers* can be considered "nonthermal".)

The radio sky includes a wide variety of sources of all of the above types, whose relative contributions vary with direction, frequency, and time. Thus, just as the Universe lacks a uniform physical temperature, the sky lacks a uniform brightness temperature. But if discrete sources like stars, galaxies, and other objects of small angular extent are excluded, the general diffuse "background" has:

- a very low brightness temperature of just a few kelvins in the "microwave window" (roughly 1-100 GHz), where the cosmic microwave background (CMB) can best be observed
- a steeply-rising brightness temperature at lower frequencies, reaching thousands of kelvins at the lowest observed frequencies (around 10-100 MHz), where synchrotron emission from our Galaxy predominates
- increased brightness at high frequencies in the infrared/sub-millimeter (THz) regime, where interstellar dust, heated by starlight, produces a different kind of Galactic background -- but here the definition of brightness temperature above breaks down, since photon energies become too large (see above).

So how "hot" the sky appears varies, and at low frequencies, it has nothing to do with real temperature, except in special cases like the CMB. Below a few hundred MHz, the brightness temperature of the sky is very warm indeed, but above a GHz or so, where one can see the CMB, the sky is truly "cold" by human standards -- much colder than the ground in fact, or any person who happens to step in front of a radio telescope!

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