# Radio Astronomy: How J.C. Bose's invention opened a new window to the Universe

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**Prologue:** Sir J.C. Bose's work in radio microwave optics was specifically directed towards studying the nature of the phenomenon and was not an attempt to develop radio into a communication medium. His experiments took place during the same period (from late 1894 on) when Guglielmo Marconi was making breakthroughs on a radio system specifically designed for wireless telegraphy. In 1895, he demonstrated the generation & reception of radio waves in Kolkata, a good 2 years before the experiment by Marconi. It is thanks to this stellar breakthrough that we are able to probe the Universe in a unique manner using radio wavelengths.

## 1. Introduction to Radio Astronomy

Astronomy is one of the oldest sciences. It started from the time mankind turned its gaze upwards to try and understand the heavens. It began with use of naked eyes which are natural detectors for light waves, but evolved dramatically with the advent of the telescope. Galileo turned the recently invented optical telescope to the heavens and revolutionised astronomy forever (figure 1). Over the times since then, optical telescopes have evolved from the simple ones that Galileo used to the large, sophisticated facilities that modern day astronomers employ.


Figure 1: Galileo and the telescope, c.1609

There are two main factors that drive the need for larger telescopes. A bigger telescope is able to collect more light, hence can see fainter sources i.e., they are more sensitive and can see more objects in the Universe. Bigger telescopes also provide higher resolution – the ability to distinguish between nearby objects or sources in the sky. The sensitivity depends on the size of the aperture of the telescope (D) and is proportional to $D^2$. The resolution depends on the ratio of the wavelength of the radiation $\lambda$ to the size of the aperture of the telescope, and is proportional to $\lambda/D$. Thus, a bigger telescope gives both higher sensitivity and better resolution.

Going beyond light waves : Light is a form of electromagnetic radiation and is part of a much wider spectrum of waves, ranging from the lowest frequency (largest wavelength) radio waves to the highest frequency (smallest wavelength) gamma rays, as shown in figure 2. The same object can emit, or be studied, at different wavelengths of the electromagnetic spectrum. Studying the same object in the Universe at different wavelengths can give different and complementary information about the object, and hence a more complete picture can be assembled. Figure 3 illustrates this with an example from studies of the Andromeda galaxy at different parts of the electromagnetic spectrum. However, there are some objects and phenomena can be studied ONLY at some specific wavelengths. Thus, multi-wavelength astronomical observations could greatly improve our understanding of the Universe.

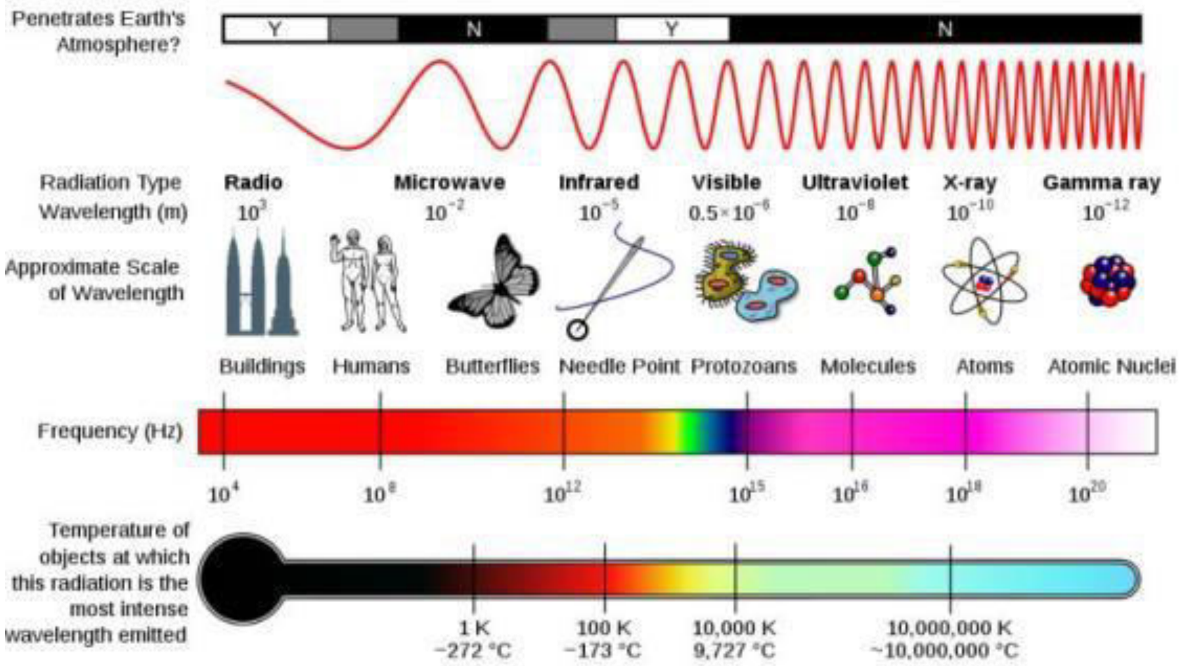


Figure 2: The Electromagnetic Spectrum

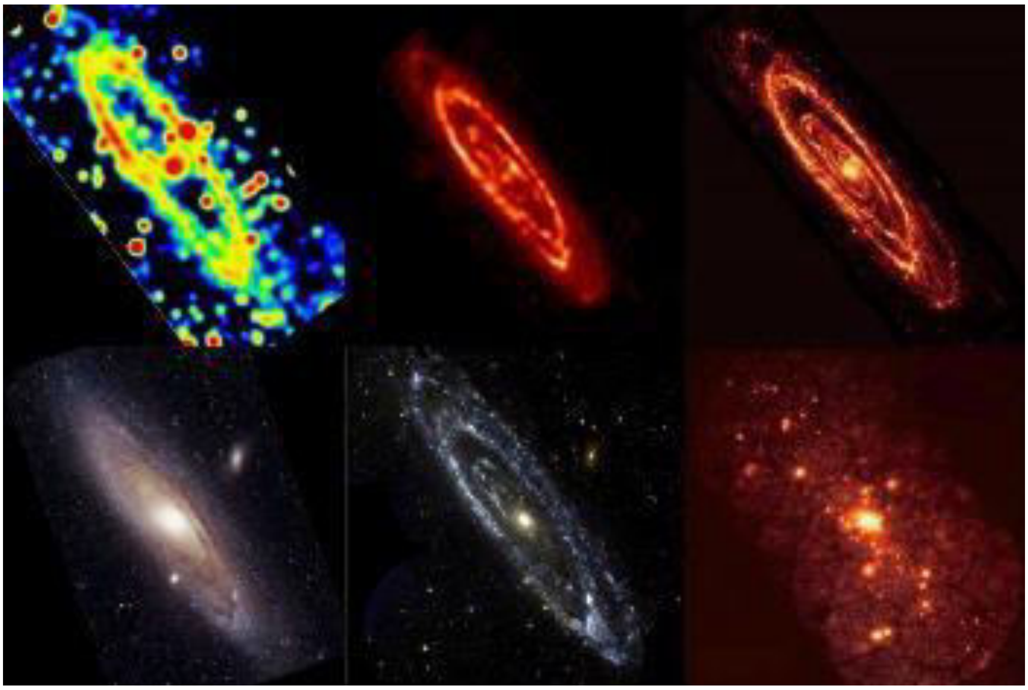

Figure 3: The Andromeda galaxy at different wavelengths – from Radio to Gamma-rays – showing different aspects of the galaxy becoming prominent at different wavelengths

However, there are some hurdles to overcome. First, we need to have the detectors for all the wavelengths. This has become possible over time with the development of technology e.g. photographic plates, charge-coupled devices, radio communication equipment. Second, not all the wavelengths from outer space reach us because of various effects in the Earth's atmosphere and ionosphere. As can be seen in figure 4, the two main Earth-based windows for astronomy turn out to be the optical window and a very wide portion of the radio window; for all the other wavelengths, we have to have space-based observing facilities. Hence it was natural that radio astronomy was the next branch to develop after optical astronomy.

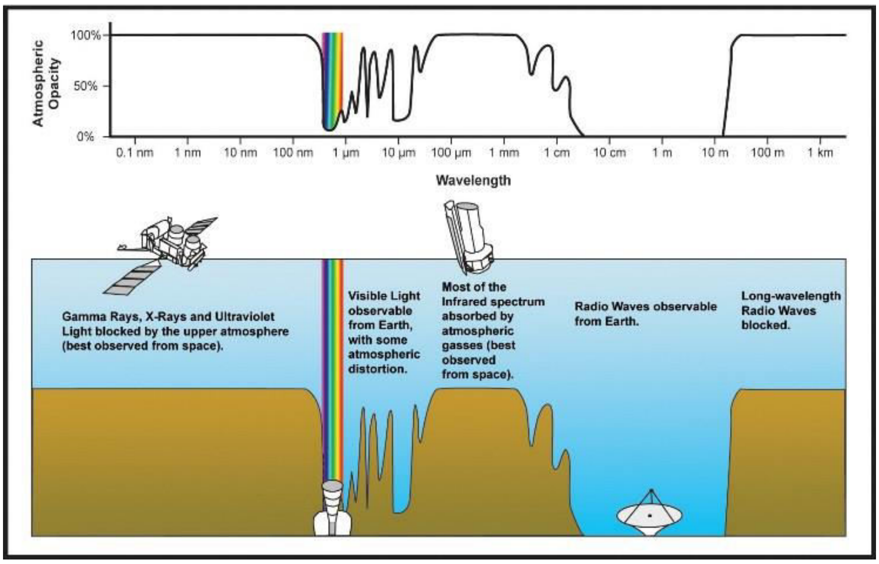


Figure 4: Multi-wavelength astronomy – Earth-based and space-based windows

**2. Radio Astronomy basics**

Genesis and early days : Detectors for radio astronomy came about during the1930s as an off-shoot of the developments in radio communications technology. As often happens in scientific discoveries (especially in astronomy), serendipity played a major role. Radio Astronomy has its origin in the Bell Labs, USA where, while debugging trans-atlantic communication systems to understand the cause of unwanted noise that was being picked up by the equipment, in 1931 Karl Jansky built an antenna designed to detect radio waves at a frequency of 20.5 MHz. It was mounted on a turntable that allowed it to be rotated in any direction (see figure 5). It had a diameter of 100 ft. and height of 20 ft. He was able to show that the source of noise in the communication system was not coming from any terrestrial source, but from a given direction in the sky -- from the Milky Way. With this breakthrough discovery, radio astronomy was born, and Karl Jansky is known as the father of radio astronomy.

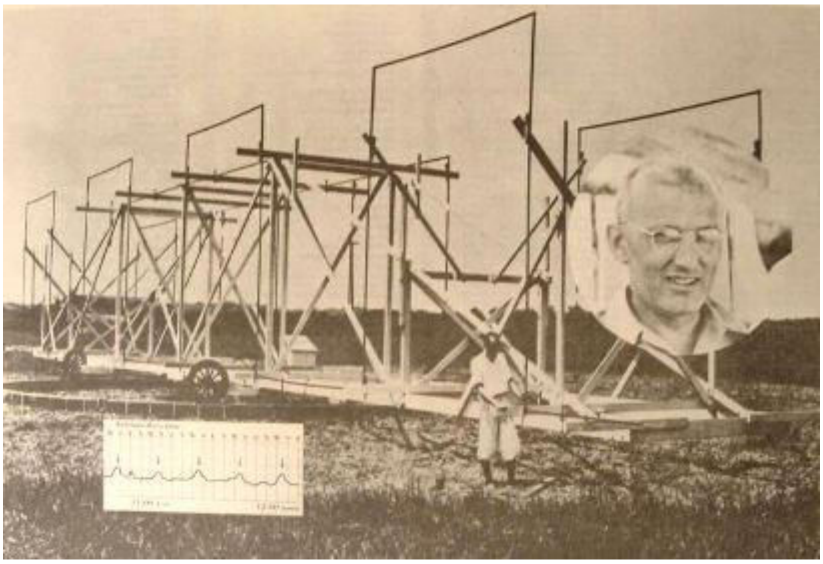

Figure 5: Karl Jansky and the first detection of radio waves from the Universe, in 1931

Basics of radio telescopes : A radio telescope antenna (figure 6) is basically like any satellite dish that we use for receiving television signals; but there is one major difference : celestial radio signals are *very* weak, so much so that we have a separate unit of flux to describe them : 1 Jy = $10^{-26}$ W/m$^2$/Hz. On this scale, the strongest celestial radio sources are about 1000 Jy, and today radio astronomy probes sources as weak as few micro Jy. Put another way, the typical input power to a radio telescope from celestial sources is ~ -100 dBm, meaning that it would take a few 100 years of continuous operation of the telescope to collect 1 milli Joule of energy. These signal levels are so weak that the typical instrumental noise levels from the receiver electronics can easily overwhelm them, making the detection of celestial sources a difficult task.

In order to overcome the above issues, radio astronomers do the following : use large antennas so as to collect as much signal as possible, use large bandwidth to increase the amount of signal (most celestial sources emit over a fairly large range of frequencies); build high quality low noise receivers to minimise the harmful effects of noise; and integrate the final signal over as long a duration of observation as possible, so as to further improve the signal to noise.

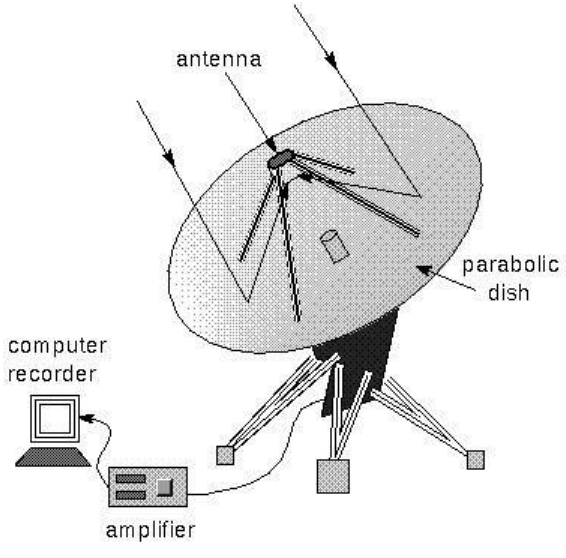


Figure 6: The basic radio telescope

<u>Single Dish vs Multi-dish Radio Telescopes :</u> From the arguments above, and our understanding that both resolution and sensitivity depend on the physical aperture size of the telescope, the goal has been to build larger and larger antennas for improved performance of the radio telescope. However, due to practical limits, fully steerable single dishes of more than about 100 m diameter are very difficult and expensive to build (see figure 7 for some examples). Now, for 100 m size radio telescope operating at a typical wavelength of 1 m (frequency of 300 MHz), the resolution ($\lambda/D$) is approximately 0.5 degree, which is very poor compared to the resolution achieved with the simplest optical telescopes !

To overcome this challenge, radio astronomers discovered the technique of aperture synthesis where, to synthesize a telescope of larger size, many individual dishes spread out over a large area on the Earth are used. Signals from such array telescopes are combined and processed in a particular fashion to generate a map of the source structure, with a resolution that is now give by $\lambda / D_s$ , where $D_s$ is the largest separation between the antennas in the array. This his allows radio telescopes to be competitive in resolution to telescopes at shorter wavelengths (like optical). Figure 8 shows some examples of some well known multi-dish aperture synthesis array radio telescopes, and figure 9 illustrates the improved resolution achieved by the use of such telescopes.

Figure 7 : the picture on the left is of the largest fully steerable single dish radio telescope in existence today – the 100-m Greenbank Telescope in USA; the other two are largest non-steerable (fixed) single dish radio telescopes : the 300-m Arecibo Radio Telescope (middle) in Puerto Rico, and the 500-m FAST observatory (right) in China

Figure 8 :  the picture on the left is of the Very Large Array (VLA) radio telescope in the USA and that of the right is the Atacama Large Millimetre Array (ALMA) located in Chile.

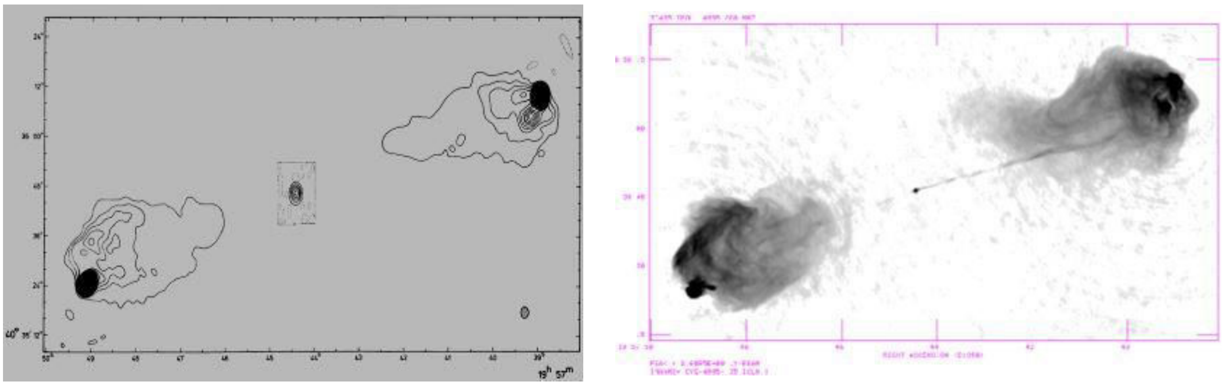

Figure 9 :  Illustrating the improvement in resolution with the advent of aperture synthesis array telescopes.  The image on the left is of the radio galaxy  Cygnus-A made with a single dish antenna; the one on the right is an image of the same galaxy made with the Very Large Array (VLA) radio telescope in the USA.

**3.  Case study of a modern radio observatory :  the GMRT**

Introduction and basic paramters : The Giant Metre-wave Radio Telescope (GMRT) is a world class facility for studying astrophysical phenomena at low radio frequencies (50 - 1450 MHz).  Completed in 1992 by the National Centre for Radio Astrophysics (NCRA), of the Tata Institute of Fundamental Research,  it is an array telescope consisting of 30 antennas of 45 m diameter (see picture in figure 10), operating at metre wavelengths  --  the largest in the world at these frequencies !

It is situated at a Latitude of  19 deg N and  Longitude of 74 deg E, about 70 km N of  Pune,   160 km E of  Mumbai.  Of the 30 antennas,  12 are located in a central  compact array and the remaining 18 are spread out along 3 arms of  Y-shaped array,  going out to distances of 14 km from the centre (see figure 11).  By appropriate combination of signals from all the 30 antennas, the resolution of a 28 km size antenna is achieved.

Figure 10 :  A  panoramic view of part of the GMRT array

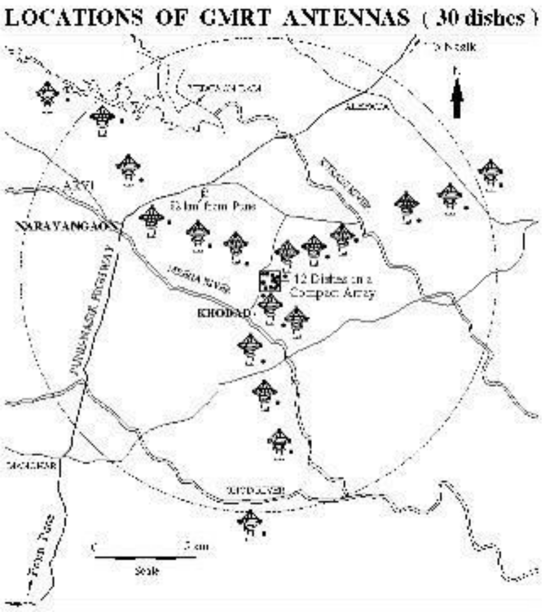


Figure 11 : Showing the layout of the GMRT array, centred near the village of Khodad and extending out to radial distances of a bit more than 14 km, along 3 arms arranged in a roughly Y-shaped configuration.

Many different sub-systems and technologies go into making an instrument like the GMRT, several of them requiring cutting-edge technologies to be developed and deployed :

1. *Mechanical sub-system*
2. *Servo sub-system*
3. *Antenna feeds (including positioning & control)*
4. *Receiver chain -- analog*
5. *Optical fibre sub-system*
6. *Receiver chain -- digital*
7. *Telemetry sub-system*
8. *"On-line" Control and Monitor sub-sytem*
9. *Off-line data processing chain(s)*

<u>GMRT : Operations, Usage & Science</u> : The GMRT observatory is open to international participation via a formal proposal system. Proposals are invited twice a year and reviewed by the GMRT Time Allocation Committee, and allocated time on the telescope. Observations are scheduled for 2 cycles of about 5 months each. The GMRT is typically oversubscribed by a factor of 2.5 i.e. the demand for observing time is more than the available time, and hence only the best proposals are allocated time. As shown in figure 12, The GMRT sees users from all over the world, with the distribution of Indian vs Foreign users being close to 50:50.

The GMRT is a powerful instrument to probe several astrophysical objects and phenomena, and the range of science possible with the facility is quite wide spread, covering topics such as:

1. The Sun, extrasolar planets
2. Pulsars : rapidly rotating neutron stars
3. Other Galactic objects like supernova remnants, microquasars etc
4. Other explosive events like Gamma Ray Bursts
5. Ionized and neutral Hydrogen gas clouds (in our Galaxy and in other galaxies)
6. Radio properties of different kinds of galaxies; galaxy clusters
7. Radio galaxies at large distances in the Universe
8. Cosmology and the Epoch of Reionization
9. All sky surveys such as the 150 MHz TIFR GMRT Sky Survey (TGSS)

*Many interesting new results have been produced in the last 17 years or so that the GMRT has been functional. Today, more than 40 papers per year are published in international journals that use data and results from the GMRT.*

*Current Status & Future Prospects* *: The GMRT has just completed major upgrade that improves its sensitivity by a factor of up to 3 times, and also make it a much more versatile instrument. The upgraded GMRT provides near seamless frequency coverage from 120 to 1450 MHz at present (likely to be extended down to 50 MHz), with a maximum instantaneous bandwidth of 400 MHz (replacing 32 MHz of the legacy system), with improved sensitivity receivers. There are also accompanying improvements in the servo system, the monitor and control system and infrastructure facilities. These upgrades will keep the GMRT at the forefront on the global stage, as one of the most sensitive radio facility at metre wavelengths, for the next decade or so.*

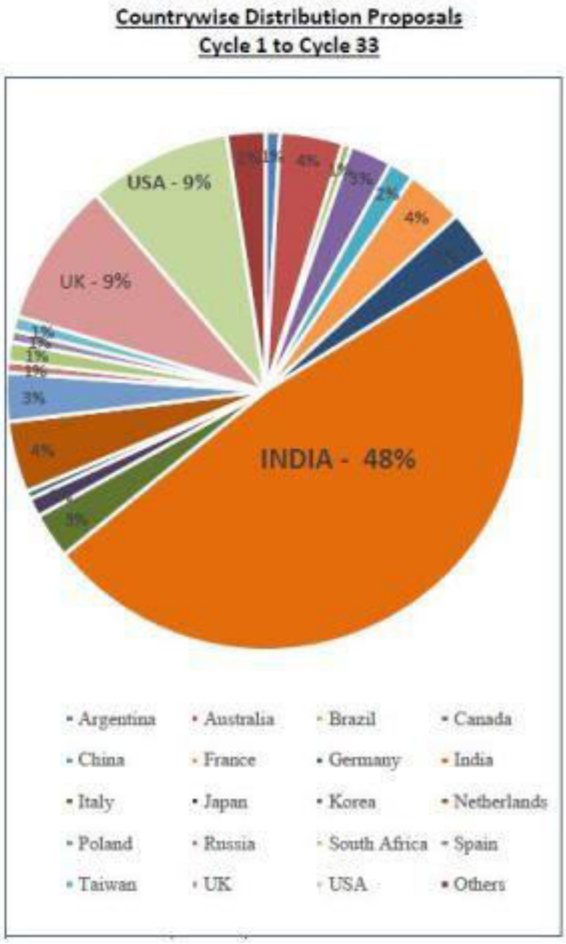


Figure 12: Proposal allocation pie-chart for the GMRT from cycles 1 to 33 (2003 to 2018), showing usage by scientists from several countries across the world, with a roughly 50% participation from Indian astronomers.

**About the author**

Prof. Yashwant Gupta presently heads the National Centre for Radio Astrophysics as the Centre Director. He obtained his M.S. and Ph.D. in Radio Astronomy from the University of California, San Diego in 1990, after completing his Bachelor's degree in Electrical Engineering from IIT Kanpur in 1985. In addition to research in the astrophysics of pulsars, Prof Gupta also has significant interest and involvement in instrumentation and signal processing applications in radio astronomy. He has led the recent major upgrade of the GMRT, and is also involved in the technical developments at the SKA, in addition to being the Science Director from India on the SKA Board.

To commemorate JCBose's birth centenary in 1958, the JBNSTS scholarship programme was started in West Bengal. In the same year, India issued a postage stamp bearing his portrait.

On 14 September 2012, Bose's experimental work in millimetre-band radio was recognised as an IEEE Milestone in Electrical and Computer Engineering, the first such recognition of a discovery in India

The Bank Of England has decided to redesign the 50 UK Pound currency note with an eminent scientist. Indian scientist Sir Jagadish Chandra Bose has been featured in that nomination list for his pioneering work on Wifi technology