Radio Astronomy
and the Investigation of the Universe

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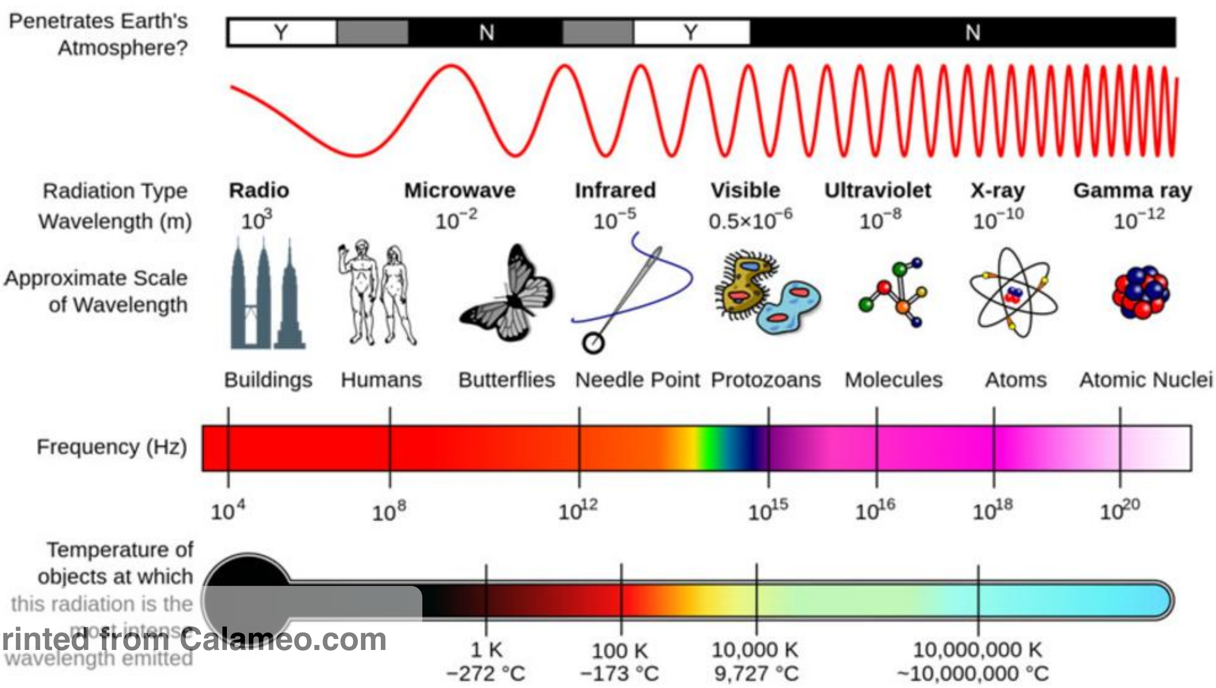
Abstract: Radio telescopes are instruments that probe the Universe through the detection and study of radio waves, which defines the science of radio astronomy. In this article I will describe briefly the science and instrumentation used in radio astronomy and give an overview of some of the current facilities.

INTRODUCTION

Most of the radiation received on Earth's surface from the Universe is not directly seen or sensed by human bodies. Our most sensitive detectors are our eyes, which collect electromagnetic (EM) radiation as visible light, whose peak is in the band that includes the yellow and green colours

Figure 1: Representation of the electromagnetic spectrum, with the corresponding transparency of the atmosphere (top) and the equivalence between wavelengths, frequencies and energies/temperatures.



(maximum at 555 nanometres). Other kinds of radiation cannot be seen from the ground, since our atmosphere is not transparent to many of these radiations, thus requesting different sensors to be detected on Earth. For instance, infrared and ultraviolet can partially reach Earth's surface, while the atmosphere is essentially transparent to radio waves, from wavelengths of tens of meters to about 1 centimetre **(Figure 1)**.

From figure 1, one might guess that radiation with longer wavelengths (shorter frequencies) are less energetic and behave like waves, while radiation with shorter wavelengths (roughly from near infrared and optical to higher frequencies) behave as particles. This different behaviour leads to different detection techniques for different EM bands. This article will discuss mostly the radio band and how it is used for radio astronomical measurements. Section 2 discusses why doing radio astronomy and what radio waves can tell us about the astrophysical processes and beyond. Section 3 describes how radio observations are conducted and what shortcomings radio astronomers have to face to do it. Section 4 describes a few current and future radio observatories and what they will bring to us, while the closing remarks are presented in Section 5.

WHY DO WE OBSERVE RADIO WAVES?

The average density of the Universe is very low, with about 6 hydrogen atoms per m3. The radio waveband is a very interesting band to observe the Galaxy and the outer Universe due to the very low absorption it suffers during its path from the emitting source to our telescopes on Earth. Also, since hydrogen is the most abundant element in the Universe, its density and behaviour (neutral first, then mostly ionised, with a small fraction of neutral atoms at present) can help astronomers trace the matter evolution along the history of the Universe. This tracing, particularly at earlier times, is primarily done through the emission in the 21cm wavelength of neutral hydrogen, which corresponds to a hyperfine transition of the electron spin.

One of the most important observations made with radio telescopes relates to cosmology and the Big Bang model: the discovery of the Cosmic Microwave Background Radiation, or CMB, in the astronomical jargon. It was detected in radio and microwave bands (from 4 GHz up to 300 GHz) and was produced when the Universe became neutral 380.000 years after the Big Bang. CMB is the oldest (and farthest) electromagnetic signal ever detected by man and was discovered in 1964 by A. Penzias and R. Wilson, using a Bell Labs antenna and, after the confirmation from other independent measurements they received the 1978 Nobel Prize in Physics. A dramatic confirmation of the black body curve expected from CMB spectrum, as well as the temperature fluctuations, or anisotropies that should be present in the primordial plasma appeared from the observations of the FIRAS and DMR instruments onboard COBE satellite. The results were announced in the early 90's and John Matter (FIRAS scientist) and George Smoot (DMR scientist) received the 2006 Nobel Prize in Physics **(Figures 2 and 3)**.

Other very important results in radio astronomy were the discovery of pulsars (1974 Nobel Prize in Physics, **Figure 4a**), the association of pulsars with gravitational waves, allowing a very restrictive verification (despite indirect) of Einstein's General Relativity Theory (1993 Nobel Prize in Physics, **Figure 4b**), the mapping of our own Galaxy, showing its spiral form **(Figure 4c)**, the detection of complex cosmic molecules of astrobiological interest, such as formic acid **(Figure 4d)** and many other organic chemistry compounds and the discovery of masers, the microwave analogue of laser emission and the very recent detection of the so-called Fast Radio Bursts, or FRB **(Figure 4e)**, cosmic bursts that releases enormous amounts of energy (~ 1040-44 W) in very short time spans (0.5 to a few milliseconds).

Finally, there is the SETI project, designed to search for radio signals from extra-terrestrial civilisations. Many of the most famous radio telescopes in the world have allocated observation time for SETI investigations with about 2700 candidates selected for subsequent observations. Despite no positive results so far, the SETI endeavour has pushed forward a number of spin-offs for radio astronomy receivers, signal processing and distributed computing, such as the SETI@Home initiative.

HOW DO WE DETECT RADIO WAVES?

Radio telescopes use receivers similar in concept to an AM-FM radio unit (or ham station) or the parabolic open TV unit used in the 60s'. Radio

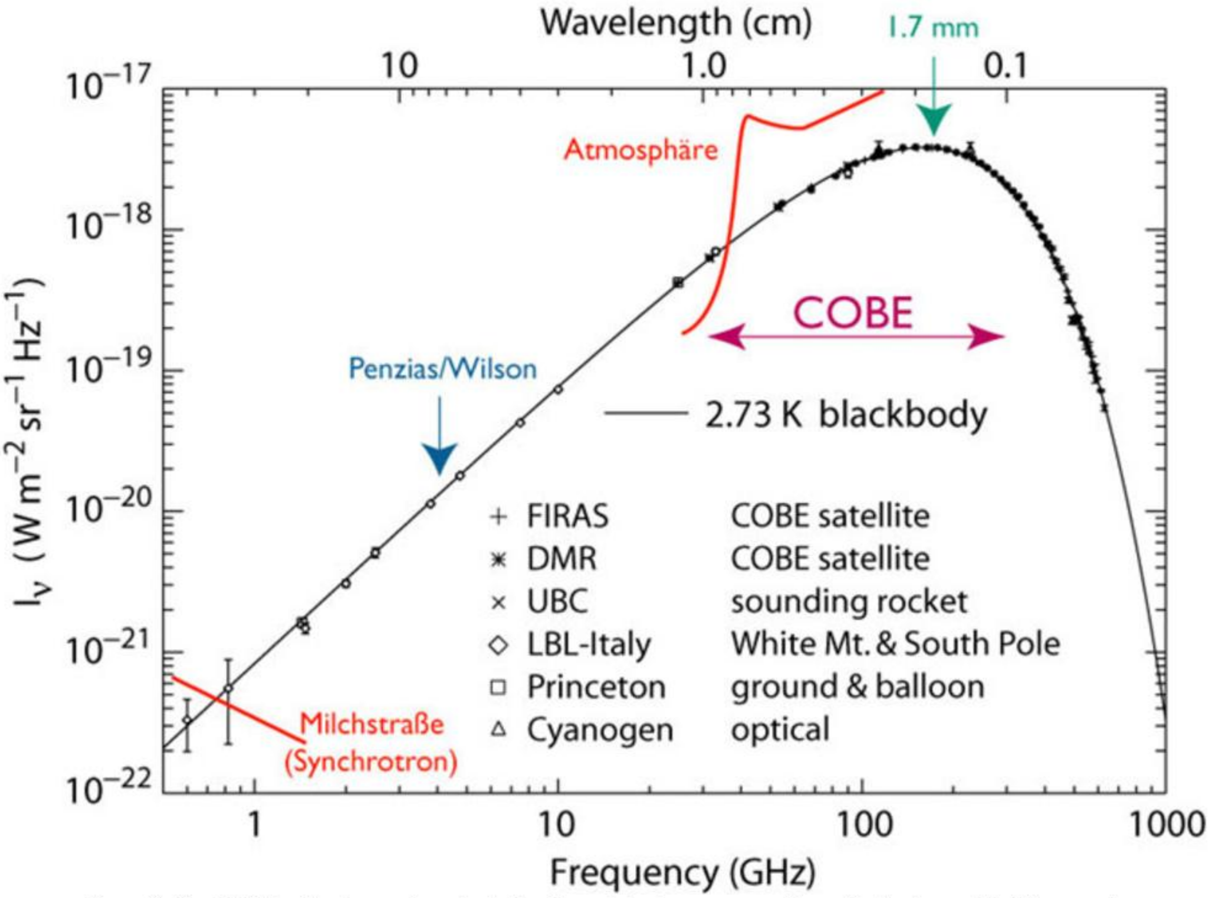
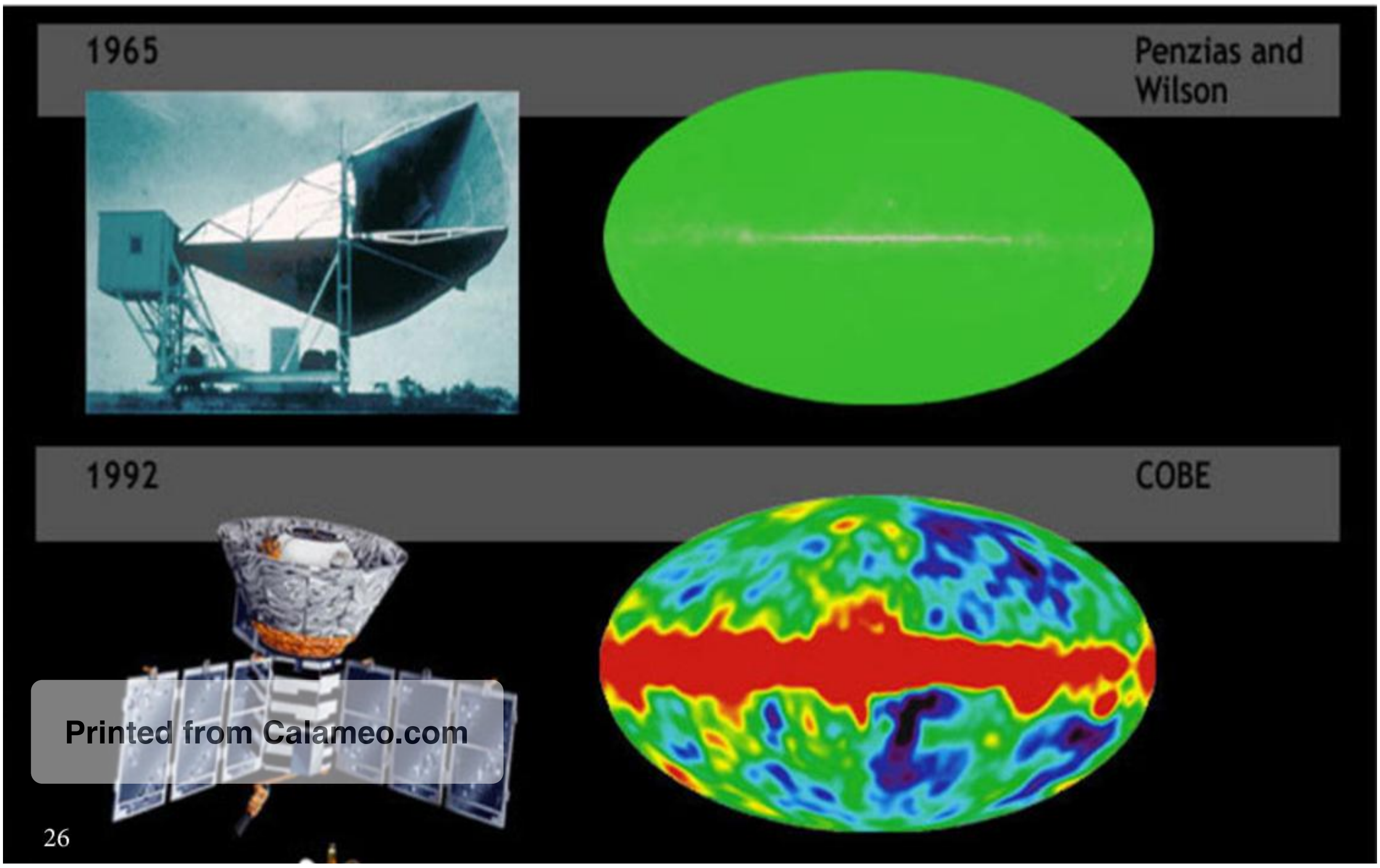


Figure 2: The CMB blackbody spectrum, including the original measurement from A. Penzias and R. Wilson and the COBE/FIRAS measurements, lead by J. Mather (Source: Pettinari, G. 2014, arXiv:1405.2280).

Figure 3: A full CMB sky as if it were measured with Bell Labs antenna used by Penzias & Wilson (top) and the actual full sky map measured by the COBE/DMR instrument led by George Smoot (Source: https://en.wikipedia.org/).



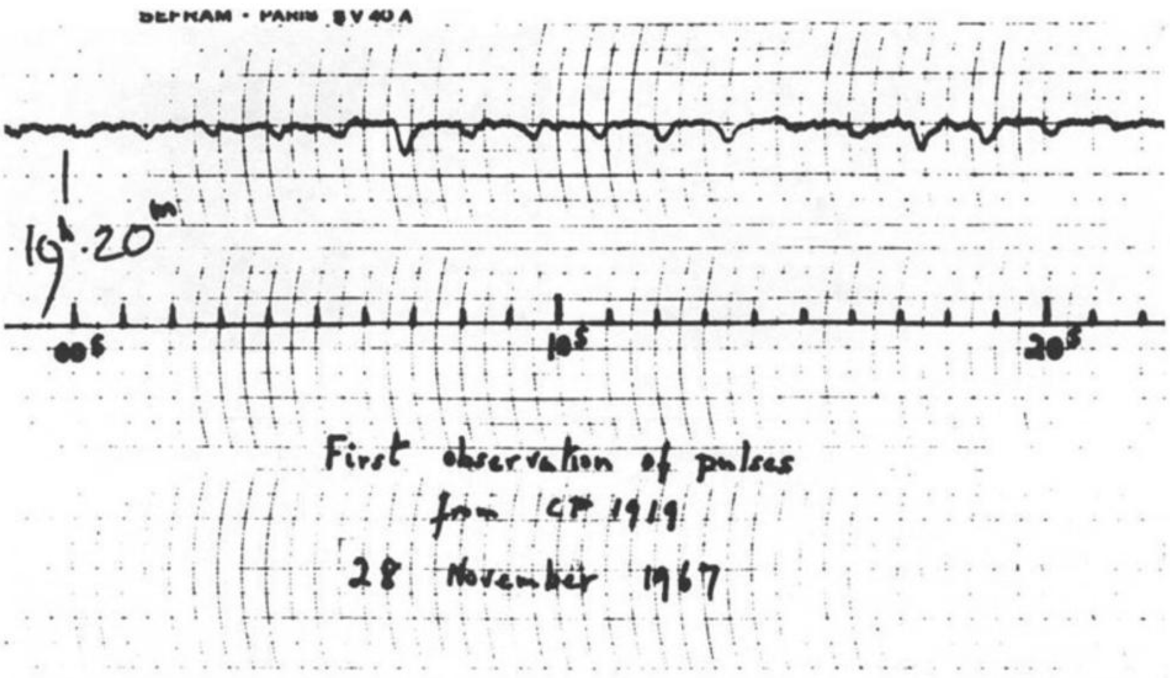


Figure 4a: Paper record of the first pulsar detection, made by Jocelyn Bell Burner, in 1968, at the Mullard Radio Astronomy Observatory in Cambridge. Antony Hewish, his supervisor and co-author of the discovery, was the 1974 Nobel Prize in Physics recipient (Source: https://arstechnica.com/science/2018/09/)

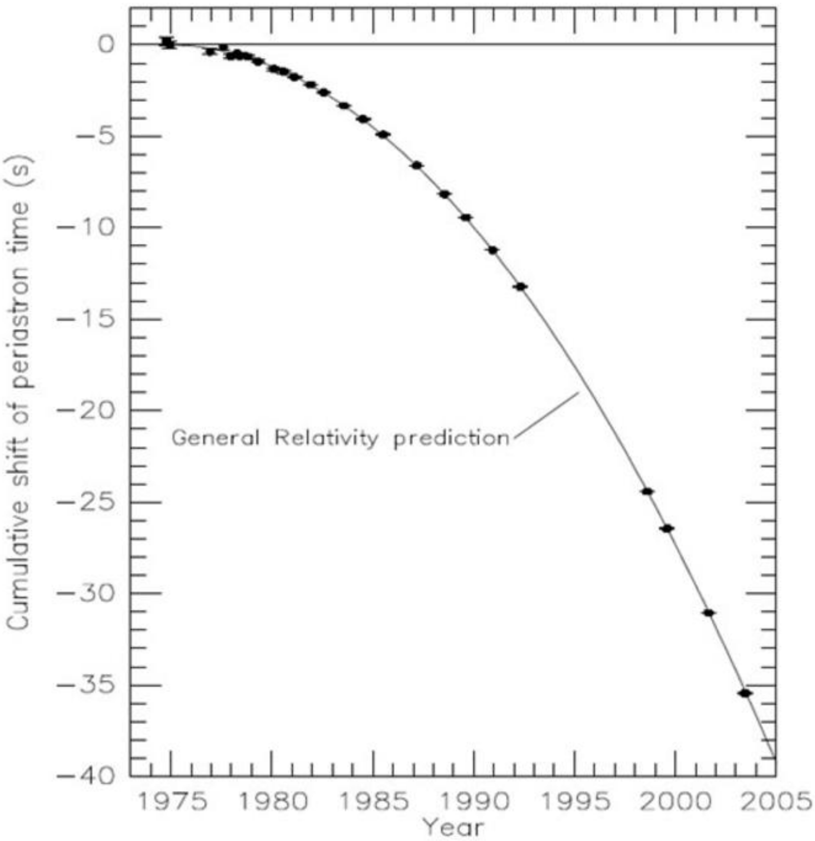


Figure 4b: Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity. (Source: Weisberg & Taylor, 2004, arXix:0407149)

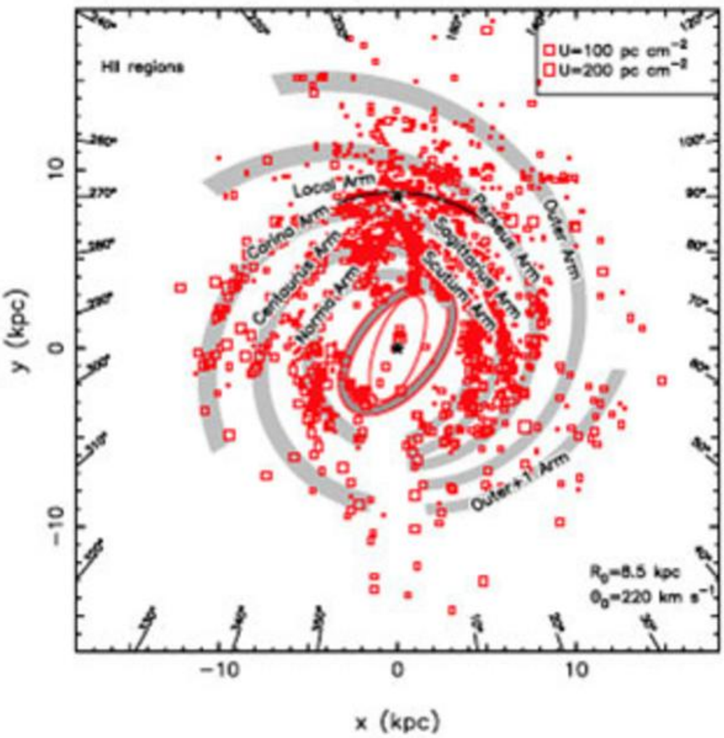


Figure 4c: The spiral structure model of our galaxy superimposed onto ionized hydrogen (HII) measurements. The sun is located at x=0, y=8.5 kpc. (Source: L. Hou & J. Han, 2014, Astron. & Astrop., 569, A125)

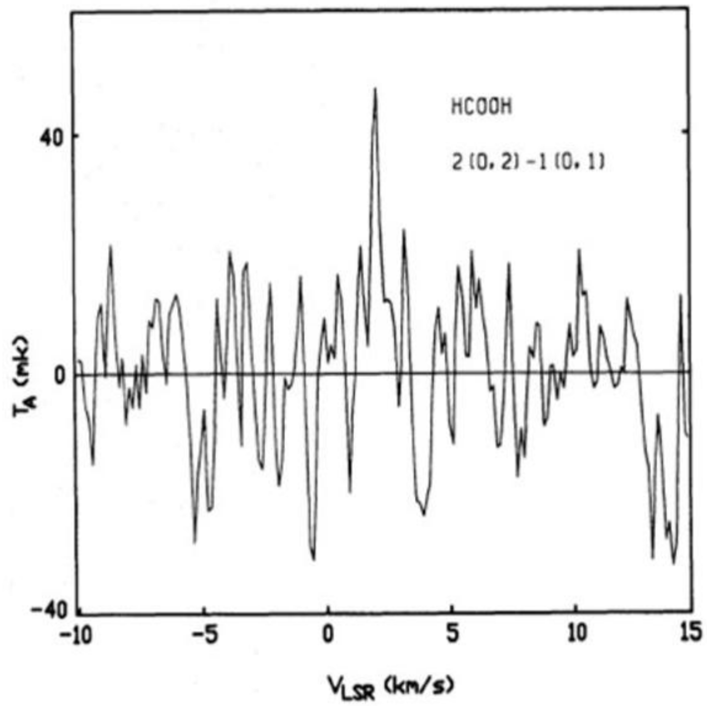


Figure 4d: Spectrum showing a line transition of the formic acid (HCOOH) towards the cold interstellar cloud L134N (Source: Irvine et al., 1990, Astron. Astrophys., 229, L9)

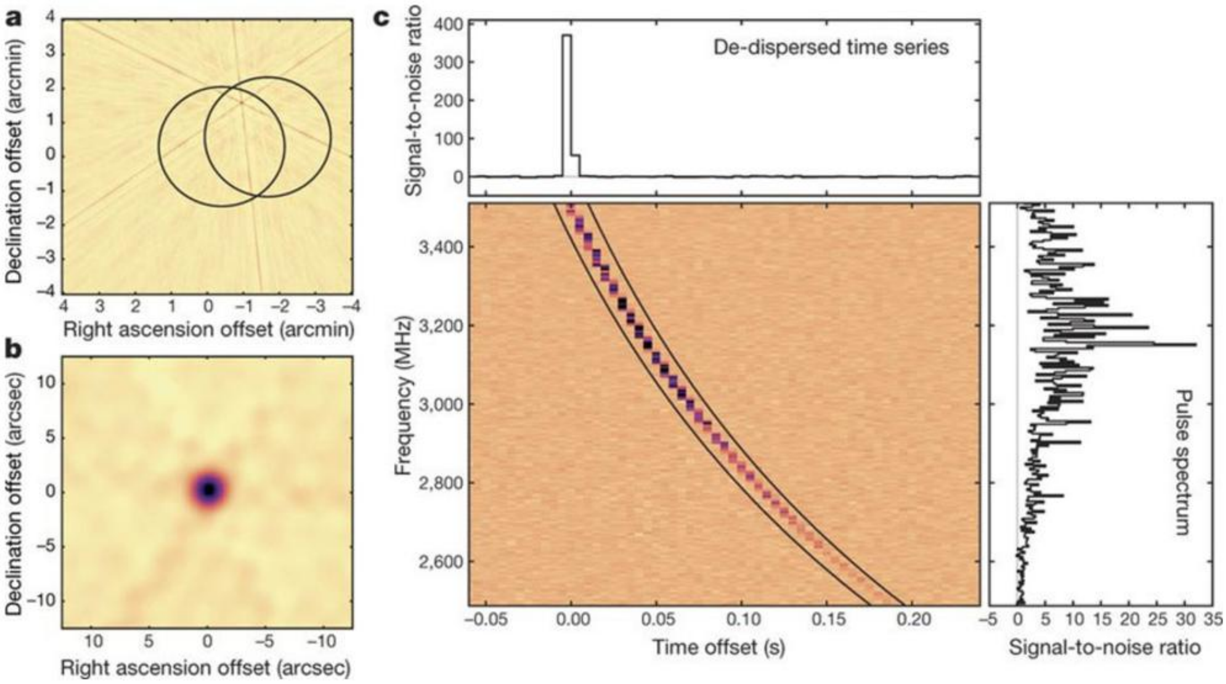


Figure 4e: First identification of a FRB as an extragalactic source. Depicted are the celestial location of the source (left), the dispersion measure of the source (centre) and the pulse spectrum of the source (right). Note the top central spectrum, where the superposition of the frequency dispersion into a single signal lasts only a few milliseconds (Source: Chaterjee et al. 2017, Nature, 541, pages 58-61).

signals coming from space are collected together with many other man-made signals from the neighbourhood (usually referred to as "Radio Frequency Interference, or RFI, in short), by a parabolic dish and fed into a receiver. The "optical system" which includes the reflector (which is the parabola) and the path followed by the EM wave to the receiver is the same followed by visible light in an optical telescope, with its Newtonian or Cassegrain configuration. Radio astronomers usually call the parabolic dish + receiver arrangement an "antenna".

Reaching the receiver, the "signal" (i.e., the wave collected by the antenna) is amplified by a low-noise amplifier (LNA), filtered by a band-pass filter, mixed with a local oscillator to allow for a simpler treatment of the signal, amplified one more time, and then integrated. Figure 5 compares a simple radio unit to a radio telescope. Antenna on the left collects radio waves, in the same way as the dish on the right. The frequency selection display in the radio unit, as well as other buttons for filtering and improving the reception, processes the electric current generated by the incoming waves before they are transformed into the sound waves we listen. The same processes of frequency selection, amplification and signal processing happen in the radio telescope before it is integrated and sent to the computer.

Figure 6 describes the receiver block with the electronics chain. In the first stage, the primary pre-amplifier (yellow box) amplifies the sky signal and sends it to the second stage, where a filter (green box) delimits the frequency band the telescope will observe. This is important, since there are protected bands for radio astronomy, defined by the International Telecommunication Union (ITU), where other radio signals that contaminate the astronomical information are kept at a minimum. In the third stage, the signal gets mixed with an intermediate frequency generator (blue and red box) and is, again, amplified by a second amplifier (red box) in the fourth stage. The need of mixing the incoming frequency with an intermediate one is necessary to lower it and make the output easier to handle.

After that the signal is fed into a detector that reads the input signal and processes the incoming power in the fifth stage. It is usually called a "square-law detector" (e.g., a diode represented by the triangle touching the vertical line) and

Figure 5: Normal home radio receiver (left) and radio telescope (right). (Source of right figure: Encyclopaedia Britannica)

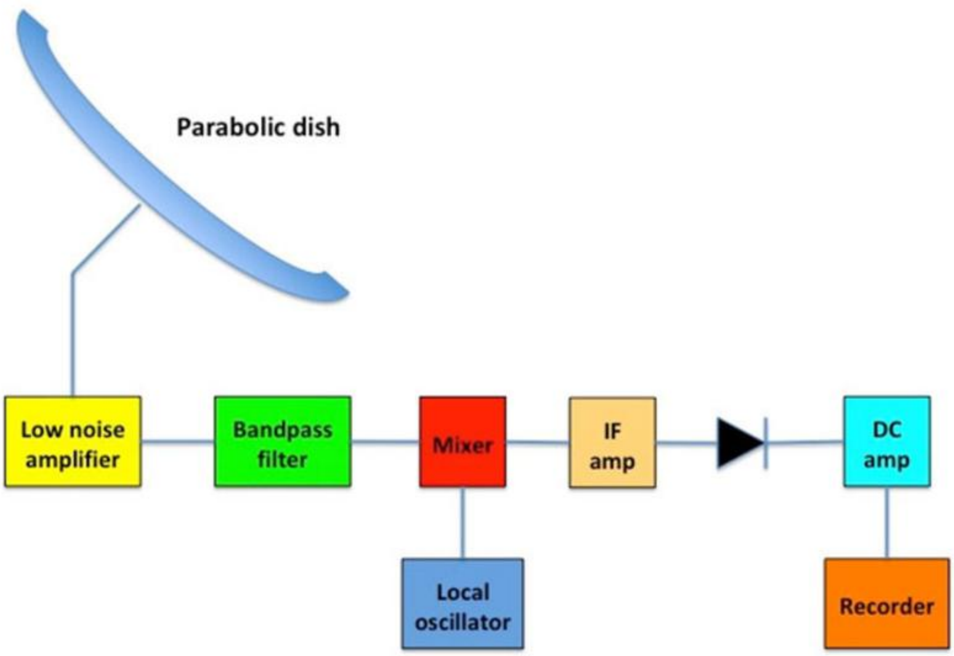


Figure 6: This is a typical receiver chain, starting from the antenna on the left. All boxes, from the low noise amplifier to the DC amp, before the signal reaches the computer are encapsulated into the receiver on the bottom right of Figure 5.

handles the incoming oscillating electric signal. This "square-law detector" squares the negative phase of incoming signal, transferring only positive signals into the DC Amplifier (light blue box, sixth stage). Finally, a conversion from analogue (electric field/current) to digital (bytes in a computer) allows the signal to be registered/processed/stored by a computer or another digital device (orange box, seventh stage). In figure 5 the recorder is represented by a computer, but this recording/ registration was done manually in the past, using charts that mechanically registered the amplitude of the incoming electric signal in paper rolls (see again **Figure 4a**).

CURRENT AND FUTURE INSTRUMENTS

Karl Jansky (1905-1950) was the person who first observed an astronomical radio source – our own Galaxy – in 1932. Twenty years later, parabolic and dipole antennas were populating the world to investigate the sky. Modern radio telescopes are made either of dipoles or parabolic reflectors. Parabolic antennas can be arranged as single-dish telescopes or radio interferometers. For longer wavelengths (a few meters to tens of meters) dipole antennas, made of long rods or wires, are more efficient. The single-dish concept is self-explanatory and comprises one parabolic dish that will feed a receiver. Radio interferometers are arrays of antennas with many dishes and coupled outputs, making up for a large parabola. Roughly speaking, the farther apart are the dishes, the larger the equivalent area of the telescope. The basic idea behind interferometry is to combine cosmic signals arriving at different antennas in different times and use correlations to produce a detailed image of the observed object. The different physical separations between interferometer antennas are referred to as baselines.

Examples of traditional single dish telescopes are the Effelsberg (Germany, 100m diameter dish), Green Bank (USA, 100m), Lovell (United Kingdom, 76m) and Parkes (Australia, 64m) telescopes (Figure 7). It is interesting mentioning that a 100m diameter dish is the largest that can be steered without compromising its structure. Think of steering a surface that could fill two soccer fields, side by side! Larger, non-steerable, radio telescopes are the Arecibo Observatory, located in Arecibo, Puerto Rico, and the FAST (or Tianyan, in Chinese) telescope, located in Guizhou, Southwest China. Both do not have direct pointing capabilities, their dishes looking permanently at a single region in the sky. They point to different parts of the sky by displacing their foci in relation to surface of the dish which are, respectively, 305m and 500m diameter. Arecibo is famous, among other things, for staging a few scenes of James Bond movie "Golden Eye".

Radio interferometers have been operating since the early 50s, producing images with better resolution than those produced by single-dish instruments, with resolutions of about 1 milliarcsecond. Baselines of a few kilometres are common in most operating interferometers in the world and some of them are capable of displacing the antennas through railroads, allowing for baseline changes. Figure 8 shows three modern interferometers operating today and the future, most ambitious radio telescope planed by man: the SKA (Square Kilometre Array).

The Atacama Large Millimetre/submillimetre Array (ALMA) is probably the most sophisticated radio interferometer in operation today, with 66 antennas of 12m diameter and 7 antennas with 7m diameter (bottom left). It is located at altitude 5000m in Chajnantor plateau, Atacama (Chile). The Karoo Array Telescope (renamed MeerKAT) is a South African based interferometer, with 64 dishes of 13.5 m (top right) and a precursor of the SKA and, as ALMA, has many technological improvements that will serve as pathfinders of SKA. The Jansky Very Large Array (VLA) is operating since the 70s, with 27 dishes of 25m, in Socorro, New Mexico (USA) and has been home of many important discoveries related to quasars and radio galaxies.

The SKA is an array, working together over tens to hundreds of kilometres and eventually thousands of kilometres. Its construction is divided into two phases: Phase 1 in Australia for SKA1-LOW and South Africa for SKA1-MID; and Phase 2 for SKA2 expanding further in Australia and South Africa as well as into other African countries. Scientific operations are scheduled to begin in the early 2020s. The SKA science will cover pretty much all branches of astronomy, from astrobiology to cosmology, and also includes fundamental physics research using pulsars.

FINAL REMARKS

Radio astronomy is a very active branch of astrophysics and has contributed to many significant discoveries in fundamental sciences, with three related Nobel Prizes in Physics, as mentioned in section 2. Since radio waves are the least absorbed form of EM waves by the interstellar and intergalactic medium, their observation and study allow us to gather information about the Universe during pretty much all of its time span, including its most ancient observable: CMB. Also, radio astronomy techniques and instrumentation are fundamental tools for space exploration, used for space probes monitoring, in the solar system and beyond (the case of the Pioneer II probe, for instance). It is also remarkable that radio astronomy research and telecommunication industry have exchanged a lot of information and many spin-offs of the former have been drifted into the commercial chain of the second.

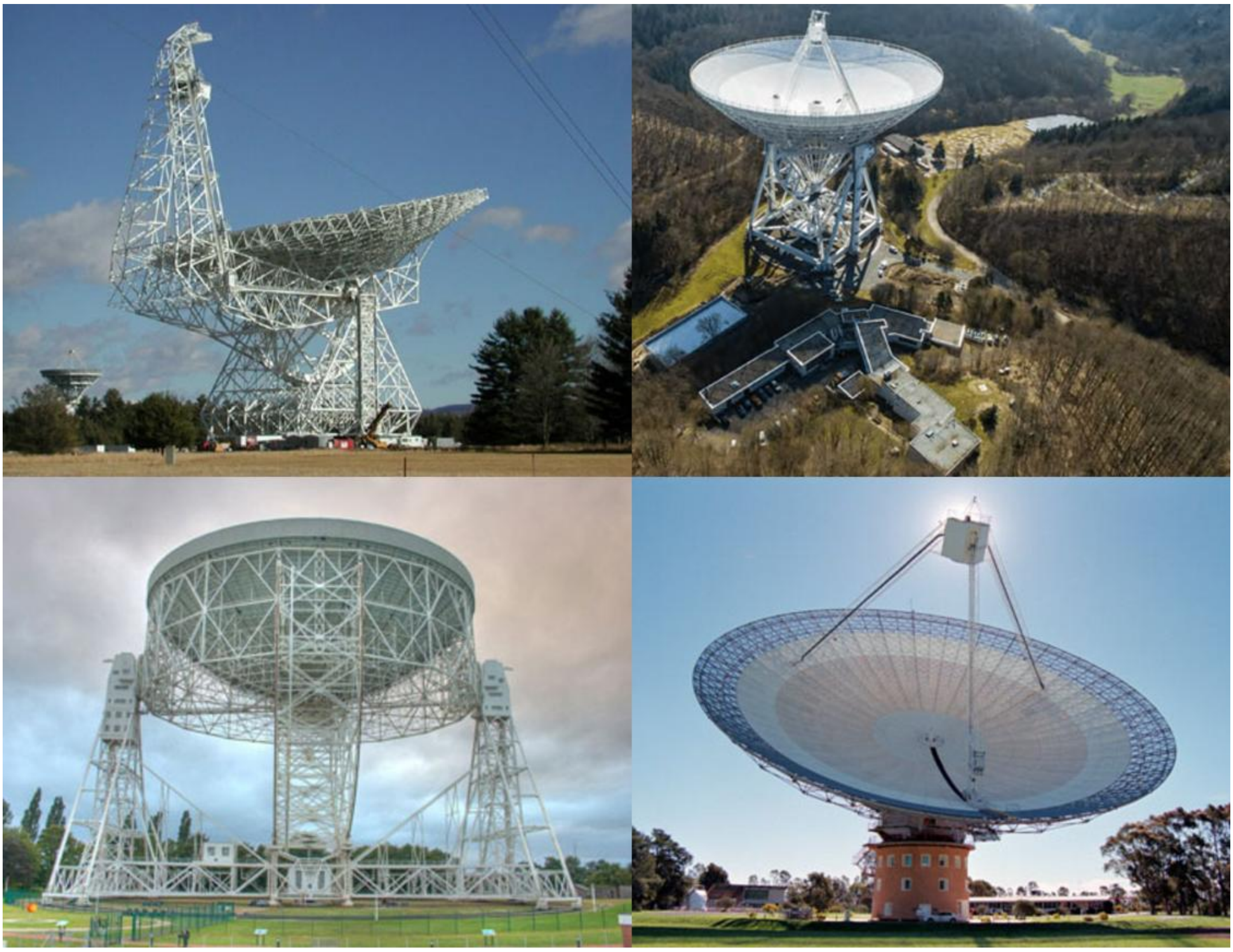


Figure 7: Single dishes: Green Bank (top left) Effelsberg (top right), Lovell (bottom left) and Parkes (bottom right).

On the other hand, the exponential increase of radio-based devices in communication, including wireless network, telecom satellites and all kinds of horizontal radio links, as well as the upcoming control systems that will be used by the Internet of Things are increasingly contaminating the radio bands protected for astronomy. In a similar fashion to what is happening with optical astronomy, where light pollution is plaguing the optical observatories near the civilization, the most competitive radio telescopes have to move to the most desert regions on Earth, such as Australian, Chilean, Chinese and South African deserts, to the Antarctic plateau (at latitude -90) and to outer space.

My personal experience of almost 30 years in radio astronomy has been a very joyful one. I mostly worked on aspects of CMB, including the collaboration with Prof. George Smoot (2006 Physics Nobel Prize) and the adventure of having observed the radio sky from Brazil, Antarctica, Russia and USA. I have participated in a number of ground based and balloon-borne experiments carried during the 90's, and am currently co-leading the construction of a radio telescope to search for baryonic acoustic oscillations (BAO) through observations of neutral hydrogen in the Universe, trying to understand the nature of the so called Dark Energy. The BINGO telescope (BAO Integrated Neutral Gas Observations) consists of a compact off-axis optical system, with two 45-m parabolic dishes, illuminating 50 corrugated horns, which are coupled to very low noise, polarization sensitive receivers. BINGO is under construction in Paraiba (NE of Brasil) and should start operation in early 2020.

The final, and very personal, comment of this article is that science progresses both through individual breakthroughs and large collaborative efforts that end up in state-of-the-art instruments, extending the human capabilities of gazing at the sky and allowing us to investigate the frontier of the observable Universe, where CMB comes from. Our society should pay careful attention to the delicate balance between high technological and scientific advancements, so that the technology that bring us comfort does not ultimately impair the scientific endeavours that yield the spin-offs that, transformed, are used to sustain and improve our civilisation.

Suggested reading

- Radio Astronomy. Kraus, J. Cygnus-Ear Books (2000)
- Advancing Astrophysics with the Square Kilometre Array (Books 1 and 2). SKA organization, downloadable from http://www.skatelescope.org/books.

Figure 8: Radio interferometers. Jansky VLA (top left), Meerkat (top right), ALMA (bottom left), and an artistic conception of SKA (bottom right).