Frequencies for radio astronomy

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Abstract:
Thanks to the transparency of the earth's atmosphere, radio astronomy observes the sky in a given bandwidth (from a dozen MHz to a few THz). As the means of observation become more sensitive, the universe can be sounded ever farther, closer to its creation. We thus discover how it has evolved over time. Radio astronomy supplies astrophysics with data, but the intensive use of the radio-frequency spectrum is restricting (even threatening) this activity. A brief description of radio astronomy's contributions to research in astrophysics and to technology and of its need for a protection of radio frequencies…

Earth's atmosphere and ionosphere are transparent for electromagnetic frequencies from 10 MHz to a few dozen GHz and for certain frequencies up to a few THz. During the first half of the 20th century, in particular during WW II, it was deemed worthwhile to have a new means for viewing the universe that would make it possible to study quite different aspects than what could be observed by using visible light. This article offers readers a glimpse of what radio astronomy can bring to scientific research and technological development. It will also shed light on the conditions related to the use of this extremely sensitive equipment.[1]

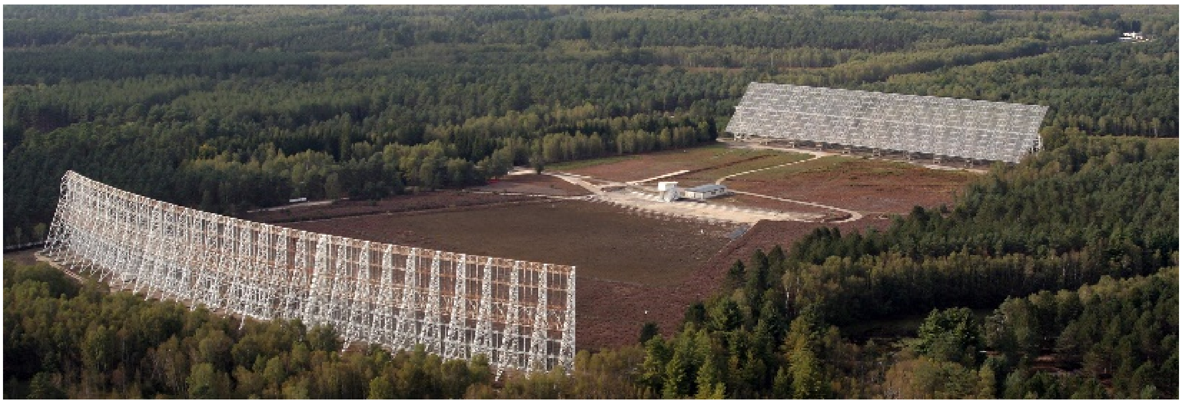
What is radio astronomy?

For radio astronomers, the sky hardly resembles the starry space seen with the naked eye. Clouds of gas, "extinct" stars that no longer emit visible light, galaxies, the universe as a whole… radio astronomy has helped change our way of looking at our cosmic environment.

Figure 1: North/south array of solar telescope antennas in Nançay (with parabolas 5-m diameter). The ORFEES spectrograph uses a single antenna of the same type.
Source: © Paris Observatory, Radioastronomy Station at Nançay.

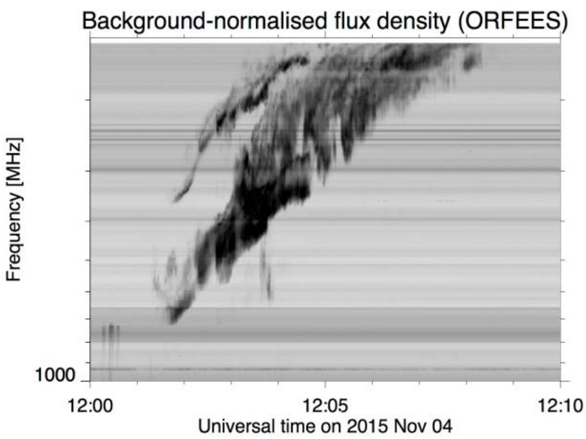
[1] This article has been translated from French by Noal Mellott (Omaha Beach, France).

Figure 2:
Fixed (foreground) and mobile (behind) mirrors of the decimeter radiotelescope in Nançay.
Source: © Paris Observatory, Radioastronomy Station at Nançay.



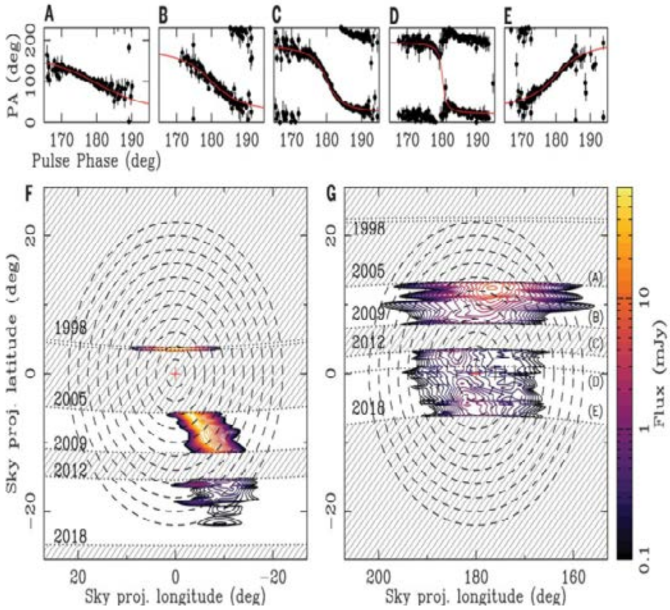
Above the visible layer of the main object in our solar system, radio waves enable us to observe Sun's much more dynamic atmosphere with its flares and mass ejections (Figure 3). Observations of the solar system offer us tools for searching for planets elsewhere and describing their environment in space. Radio observations of emissions that are not thermal but produced by the movement of electrons in the magnetospheres of Jupiter and Saturn can be used to explore magnetic fields and the interaction between a planet and its satellites. Radio emissions from a comet tell us about its chemical composition, including the many molecules that can only be observed in millimeter wavelengths.

Figure 3: Radio emission from a shock wave in Sun's corona. The vertical axis shows the frequency between 1 GHz (bottom) and 140 MHz; and the horizontal axis, the time. The higher the received emission, the darker the color. The shift from high toward low frequencies reflects the movement of the wave from the base to the top of the corona. Most of the horizontal stripes are residues of terrestrial emitters.
Observation: ORFEES spectrograph, Nançay Radioastronomy Station.
Source: © Paris Observatory, Nançay Radioastronomy Station.



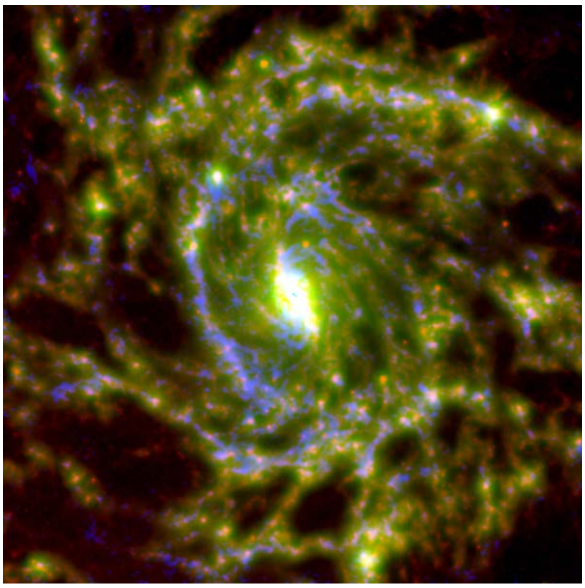
Unlike visible light, ordinary stars do not emit the most "brilliant" radio signals. However radio frequencies help us observe the final stages in a star's evolution. A pulsar is the compact mass left after the star has released energy through nuclear fusion. The signals received from such a rapidly rotating object are used to make precise measurements of it (Figure 4) and of the space crossed by the radio waves. Monitoring frequencies over a period of several years is a valuable way to detect, for example, gravitational waves.

Figure 4: An analysis of the polarization of the pulses of radio emissions from a pulsar (received by radio telescopes at Arecibo and Nançay). The emissions come from one of the star's magnetic poles (the plus sign at the center).
Source: DESVIGNES *et al*., *Science* 365, 1013 (2019). Reproduced with the permission over the AAAS.



At the other end of the evolution of stars, observations in millimeter wavelengths made with ALMA in Chile reveal clouds of gas in the galaxies where new stars are being formed. The image of the formation of a planetary system is the best ever made (Figure 5). It shows us the condensation in a disk of dust and debris around the contracting proto-star, a condensation that will beget future planets. These observations have introduced new factors that theories about the formation of planets now have to take into account.

Figure 5: IC 342, a spiral galaxy in the constellation of Camelopardalis. NOEMA has captured an image that, with a precision never attained previously, shows the distribution of clouds of dust and, thereby, the regions where stars are forming in the galaxy.
Source: © IRAM /A. Schruba /J. Pety, NASA /JPL-Caltech, NASA /JPL-Caltech /J. Turner.



For a long time now, the movements of distant objects can be tracked thanks to observations of the 21-cm band (1.4 GHz) of neutral hydrogen and its Doppler effect as a function of the radial velocity of the emitting object. We have thus learned that clouds do not rotate around the center of a galaxy as predicted by Kepler and Newton unless a huge quantity of matter in the universe is invisible to us. This has opened a new branch of research in astrophysics on “dark matter”. The same technique enables us to measure the apparent speed at which a galaxy is moving away from us, evidence of an expanding universe. With large shifts that move the band from 1.4 GHz to below 150 MHz, we try to identify the time and signature of the formation of stars in the universe by measuring the quantity of neutral hydrogen as a function of time.

The movements of heavenly bodies around the center of our galaxy lead us to think that this center is a gigantic black hole, an object made up of collapsed stars. By combining telescopes distributed over Earth (including IRAM’s 30 m telescope in Spain, which is the array’s most sensitive antenna), radio astronomy has yielded the first image of what lies close to a black hole. On this image is a ring of light around a black hole in another galaxy, the hole’s gravitation amounting to billions of times our sun’s mass.

The value of radio astronomy for society

Apart from understanding the physics of the universe with its conditions that affect our lives, radio astronomy directly contributes to the economy and technology. The weakness of the signals to be detected has led to developing, on the one hand, receivers with very low thermal noise (10 K) and several applications in the 10 MHz-1 THz bandwidth and, on the other hand, spectral analysis systems for very wide bands. Thanks to radio astronomy, we have learned to control passive radiometry for Earth observations and measure geophysical parameters: the temperature, composition of the atmosphere, distribution of water vapor, etc. Other spinoffs have been the machines used in the medical sciences: the thermograph of the human body in millimeter wavelengths, the detection and location of cancerous tumors in centimeter wavelengths, tomography with X-rays, etc. Interferometric and astrometric measurements help improve geolocation for the study of continental drift or of variations in Earth’s rotation or for satellite navigation (GNSS).

The scientific study of solar activities has also proven useful to technology, in particular the devices on board satellites. Disturbances of radio transmissions through Earth’s ionosphere have direct effects on HF communications and GNSS systems. The surveillance and monitoring functions that are being introduced in international civil aviation and the armed forces have to take account of observations from this monitoring of activities on the sun. The radio spectrum is a gateway for obtaining data since it is sensitive to solar disturbances. In France, space meteorology involves cooperation between radio astronomers and the air force.

In need of protected frequency bands

Some observations in radio astronomy are based on measuring the spectrum as a continuum or on detecting spectral lines in this continuum. For measurements to precisely determine the spectral distribution of rays, frequency bands are needed every octave starting from about 10 MHz (with a minimal width of 2%, ideally 10%, of the central frequency). By studying spectral lines that tell us about the emission or absorption of frequencies, atoms and molecules can be identified; and variations in emissions in the universe, analyzed by using the Doppler effect. These observations require protecting specific bandwidths (of the same magnitude as for measurements of the continuum).

The ITU allocated the first bands for "*radioastronomy services*" in the 1960s, when technology, receiving stations and communication systems were exclusively analog with small bandwidths on a radio spectrum that was not heavily used and had few restrictions. The bands allocated as a "*primary service*" were well protected, thus ensuring the quality of observations. The less protected bands (as a "*secondary service*" or under plans with technical specifications) were useful for observations on condition that other radiocommunication services not put the band to heavy use. The frequencies for radio astronomy services were gradual raised, as several new bands were allocated above 76 GHz, a decision made by the World Radiocommunications Conference in 2000. Current uses of the spectrum focus on the millimeter bands: mobile (5G) and satellite telecommunication services up to 70 GHz, and geolocation beyond 70 GHz. These allocations must be compatible with the millimeter wavelengths used by observatories.

Significant changes have also occurred above 65 GHz: for science, owing to the improved performance of instruments (sensitivity, the bandwidths to be observed); and for radiocommunication services, because of the shift toward digital, complex modulations using spread spectrum techniques, not to mention the denser use of the bands already allocated.

The Table of Frequency Allocations in the ITU's Radio Regulations should be modified in favor of radioastronomy by widening the protected bands (beyond 2%), increasing the protection of certain other bands (*e.g.*, below 1.4 GHz) or even allocating new bands (*e.g.*, below 100 MHz). Another possibility is to enhance the compatibility with radiocommunication services by introducing stronger restrictions on them in the classified zones around observatories.

Figure 6: The NOEMA antenna network of IRAM on Bure Plateau

The radio astronomy observatories in France are the station in Nançay (Cher department) for observations below 20 GHz, and NOEMA, the millimeter observatory on Bure plateau (Hautes-Alpes department) for observations above 20 GHz.

Extremely sensitive equipment with very restrictive conditions

Radio astronomy stations can receive and measure signals with a power up to one million times weaker than the noise coming from the stations' receivers, or from the earth and its atmosphere. They can do this by using time-averaging methods (for long periods up to dozens of hours) and on condition that their receiving equipment is stable. Radio astronomy fully depends on natural, uncontrollable signals from the heavens that convey information about their sources (and about the complexity of the universe) via the signal's frequency profile, dynamics, modulation, periodicity, duration and very existence. This information can be used to detect life on other planets or investigate transient phenomena.

The ITU-R's recommendations (RA.769, RA.1513), which concern thresholds of interference and acceptable rates of data loss for radioastronomy, set relatively strict limits for other radiocommunication services. Disturbances coming from bands adjacent to the bands used for radioastronomy are the hardest to identify, even though the antennas of telescopes detect them. These are the disturbances that will likely increase along with the number of terrestrial communication networks, the launching of constellations of satellites, the proliferation of roaming "short-range" transmitters (connected devices, radar, drones, etc.), and the effects of an aggregation of power. The guard bands [unused part of the spectrum between allocated bands] must be preserved as much as possible; and the instruments used by other radio services have to be compatible with radioastronomy, from the very phase of product design, when standards are drafted. In most cases, this also means controlling the location of transmitting devices in relation to observatories.

Conclusion

Astrophysics conducts observations using multiple wavelengths and a multitude of signals. Radio astronomy is an original technique; it has built big (even intercontinental) interferometric instruments and thus overcome the limitations related to small angular resolutions and wavelengths. Big interferometric instruments are the key. In Europe, LOFAR (a low-frequency array telescope with its core antennas in the Netherlands and other antennas in nearby lands, including France) can now produce images from the lowest frequencies detectable from Earth. The new Atacama Large Millimeter/submillimeter Array (ALMA) telescope in Chile has recently been delivering unprecedented observations from the millimeter wavelengths. The future of radio astronomy on the ground is in the works: the Square Kilometer Array (SKA) telescope now being built will be the most sensitive interferometer on centimeter-meter wavelengths.

In France, the Nançay station on centimeter-meter wavelengths has a new interferometer NenuFAR. IRAM's northern extended millimeter array (NOEMA) near Gap, the telescope most sensitive to millimeter wavelengths in the Northern Hemisphere, is playing a part in these developments. Alongside these big instruments, older, smaller installations are still operational for specific tasks such as monitoring pulsars, planets or the sun. All these instruments provide information for the international community of scientists.

A condition for carrying on these activities is that frequency bands be available for observations, free of harmful interference in areas near observatories. Given the ever denser use of the spectrum and the allocation of ever more frequency bands, international and European regulations about the bands to be assigned to radio astronomy have to constantly be updated. In addition, the areas around observatories must be more strongly protected, in particular against potential disturbances from short-range mobile devices. This might imply, for example, adopting European and national standards for building switches into these devices, so that the latter be automatically turned off in areas around observatories. Thanks to these "classified" areas and the better protection provided to them, modern radio astronomy could continue conducting observations in the bands already allocated but with less regulatory protection; this could be a response to the need for broader bands.