RADIOASTRONOMY: A GLANCE AT RADIO SOURCES IN THE SKA ERA

If you are reading this, you probably already know that one of the main goals of the **NEANIAS** space services is **providing efficient solutions** to deal with the data tsunami that will be produced by the **next-generation all-sky surveys,** with a special focus on the radio ones. With the square kilometer array (SKA) just around the corner, its pathfinders and precursors are already providing a **glimpse of what to expect in the coming years**. In particular, instruments such as MeerKAT in South Africa or ASKAP in Australia, thanks to their excellent sensitivity, angular resolution and survey speed, are pushing forward our knowledge of the radio sky, revealing a plethora of previously undetected radio sources, both galactic and extragalactic. But **what is exactly a *radio source***, you might ask? Well, to answer such a question, nothing better than a **quick tour** to discover what we see when we look at the sky with "radio glasses".

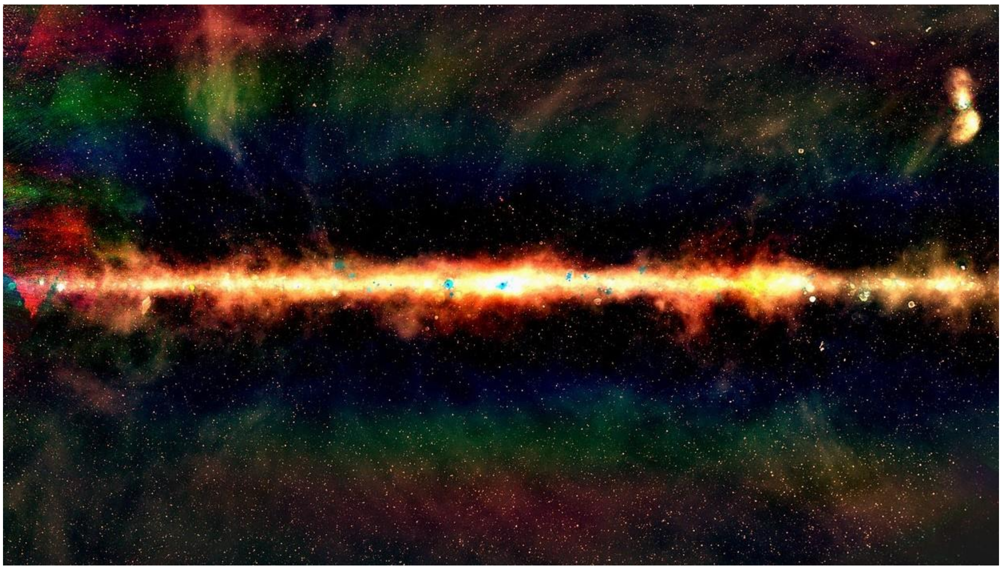
Telescopes detect **electromagnetic radiation** -that means light- that is produced by astrophysical phenomena. **Different phenomena emit light at different wavelengths.** This is crucial because it gives birth to the different branches of observational astronomy: we have high-energy astrophysics (dealing with gamma and X-rays), UV, optical and infrared astronomy and, for the sake of this article, **radio astronomy**. Each branch provides a different piece of information about the processes and sources we study, so they are **complementary**: this is the power of multi-wavelength astronomy. Visible light (the one our eyes can catch) has a wavelength roughly comprised between 400 and 700 nanometers. Likewise, wavelengths around a millimeter and longer are considered radio wavelengths, and they have a **fundamental advantage** over other wavelengths: they can pass through the Earth's atmosphere quite easily, pretty much like visible light. This means that, while the atmosphere is relatively opaque to the infrared, or (happily for us) the UV, **radio waves can reach the surface** almost unaltered. This is the so-called radio window, the main reason we can have our radio observatories on the ground, instead of putting them in orbit – which would be much more expensive and inefficient.

To catch radio waves, we use antennas. Despite looking so different from a "traditional" telescope, they work pretty much the same way: at the end, they are just "optical" devices, following similar physical laws. Nevertheless, with radio antennas, size matters: a bigger antenna provides better sensitivity (meaning it is able to catch weaker signals) and higher angular resolution (so it can distinguish finer details). The problem, then, is obvious. Due to mechanical limitations of size, weight and operability, we cannot build an arbitrarily large antenna to provide an arbitrarily high resolution…

…except for the fact that ***we can***. In some way. The technique known as *aperture synthesis*, developed by the **Nobel prize winner** Sir Martin Ryle, is a type of interferometry that allows for **combining the signals from several antennas** that simultaneously observe the same source, so that they work as a "synthesized" or "virtual" antenna, that provides an angular resolution equal to that of **an antenna as big as the maximum separation between individual antennas**. Radio telescope arrays, such as SKA and its pathfinders, and others like ALMA, ATCA or the VLA, exploit this technique to provide resolutions comparable to that of optical telescopes.

*Ellie, protagonist of the movie 'Contact' (1997), listening to radio waves at the Very Large Array. Important side note: radio astronomers **do not listen to radio waves**. It is just an artistic license.*

SKA and its precursors will mainly operate in a small fraction of the radio band, the so-called low frequency regime, **detecting wavelengths between 3 and 30 cm**. At these wavelengths, what we see is emission from *thermal* processes (i.e. depending on the temperature of the emitting object), such as the so-called *free-free* emission from ionized gas, as well as from non-thermal processes (unrelated to the object's temperature), such as *synchrotron* radiation.



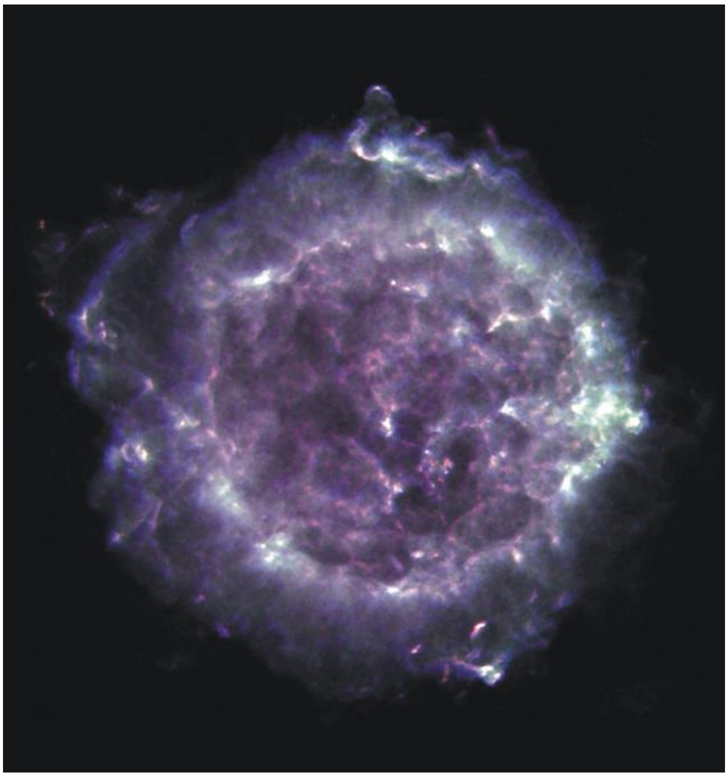
The central part of the Milky Way, as seen by the GLEAM survey. Red indicates low-frequency, Green mid-frequency and Blue high-frequency. Credit: Natasha Hurley-Walker (Curtin / ICRAR) and the GLEAM Team.

Now that we are familiar with a few basic concepts, we can dive into the wild and see what we can fish in the **all-sky surveys provided by these instruments**.

First, we have **HII regions**, where HII means "ionized hydrogen". They are enormous gas clouds that trace *stellar nurseries*, the **birthplace of massive stars**. These stars, young and extremely hot, ionize the surrounding gas by means of their intense UV fields, stripping electrons from the hydrogen atoms and **producing intense free-free emission**. HII regions are among the most numerous extended radio sources in the galaxy, being particularly abundant in the spiral arms, where most of the star formation takes place. A similar pattern is observed in other galaxies. The Orion Nebula is maybe the best example we can find of how an HII region looks like.

We will also see lots of point-like sources. Many of them will trace **Planetary Nebulae**. Despite their misleading name, planetary nebulae have nothing to do with planets. They are a type of emission nebula that is **produced by low and intermediate mass stars** (< 8 solar masses). As they approach the end of their lives, these stars expel their outer layers, forming an expanding envelope of gas and exposing the central object, a degenerate core that will eventually (and peacefully) become a **white dwarf**, the stellar evolution endpoint for this kind of stars. Radiation from the central object illuminates and **ionizes the expanding envelope**, producing free-free radiation for a few thousands of years.

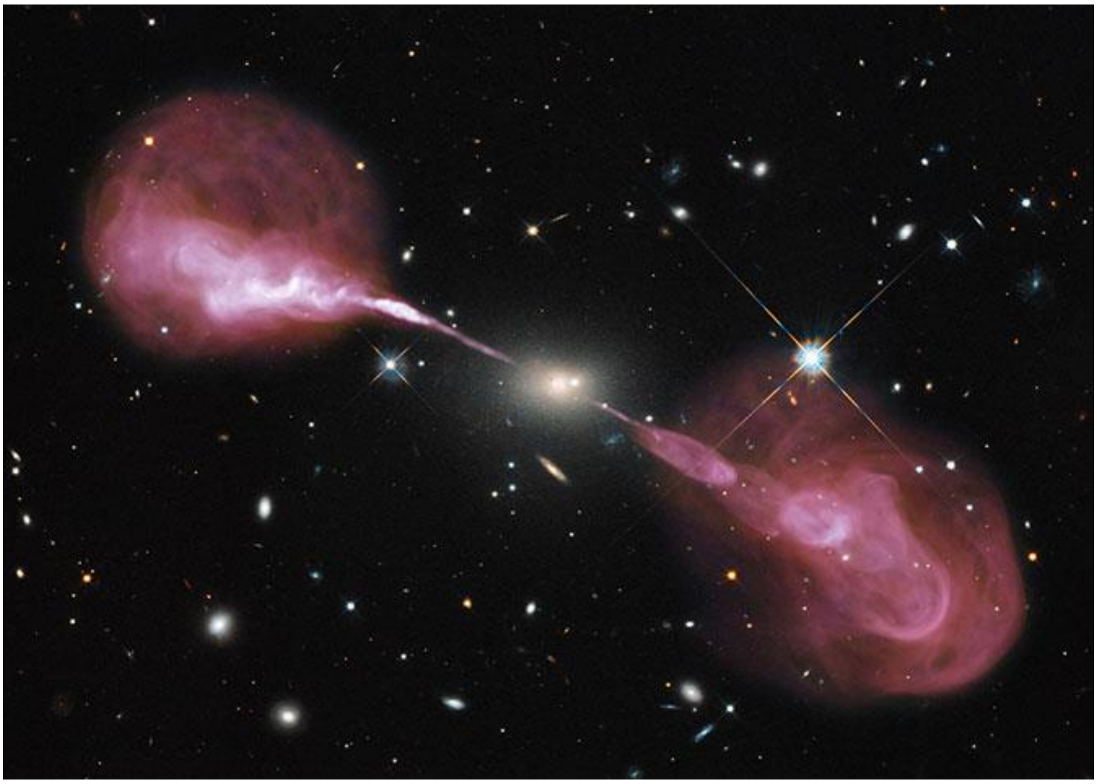
While the evolution of low and intermediate mass stars is more or less predictable, the **fate of massive stars is much more thrilling**. The most massive stars go through a series of intermediate phases when they run out of hydrogen. These transitional, unstable stages, which include the **Luminous Blue Variable** and the **Wolf-Rayet phase**, are characterized by heavy mass-loss: the stars **shower their surroundings with dust and gas from the stellar interior** through dense winds and occasional eruptions, creating spectacular nebulae, shells or envelopes. In essence, these envelopes are like an overpowered version of planetary nebulae, but with the star not becoming an "inoffensive" white dwarf. Instead, it **keeps burning heavier elements** in its core, until reaching iron, a dead end: iron fusion is an endothermic reaction, so the star cannot produce more energy, the radiation pressure stops and the **star collapses under the pull of its own gravity**, resulting in a violent supernova.



Composite VLA image (1.4, 5.0 and 8.4 GHz) of the supernova remnant Cassiopeia A. Image credit: NRAO/AUI/NSF. Investigators: L. Rudnick, T. DeLaney, J. Keohane, & B. Koralesky; image composite by T. Rector.

Supernova are, indeed, the most energetic phenomena known in the Universe. These cataclysmic stellar explosions, without diving into the details, can occur by virtue of two processes: either a massive evolved star runs out of nuclear fuel and **collapses gravitationally** (as described above), or a white dwarf in a binary system **accretes too much matter from its companion**, violating the Chandrasekar's limit and exploding. Either case, the result is the same: devastation. The star can rip off completely or leave a compact object (a neutron star or a black hole), **pouring the interstellar medium with heavy elements and large amounts of energy**, influencing nearby star formation. Precisely these remains are what we know as **supernova remnants**: stellar ashes expanding away and dissipating into the space. Supernova remnants constitute some of the most spectacular radio sources. They emit substantial amounts of **synchrotron radiation due to the shockwaves** derived from the explosion. Currently, we know more than 300 supernova remnants in the Milky Way, and a bunch of them in other galaxies. Cassiopeia A, in the image, is a great example.

Finally, if we look at the background, far beyond the Milky Way, the radio sky is filled by **thousands of radio galaxies**, like Hercules A, the one shown in the image below. Most of them have a peculiar "double-lobed" morphology. What we see is actually synchrotron radiation from the **relativistic jets produced by the central black hole**.



Composite image of the radio Galaxy Hercules A, combining optical data from Hubble and radio data from the VLA (in magenta). Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA).

These are just a few examples of the most spectacular radio sources that one can spot in the radio sky. The Universe is populated by many other types of radio-emitting sources: protostars, radio stars, pulsars, accretion disks around black holes, etc. Hopefully, **SKA will allow us to better understand these objects**, and, who knows, maybe even discover entirely new phenomena.

The activities carried out in NEANIAS are providing us with novel tools, distributed over different European Cloud infrastructures, to tackle these studies. SPACE-VIS allows us to analyze large radio maps, cross-correlating the information coming from different surveys and catalogues produced at different wavelengths. SPACE-MOS enables the possibility to handle large scale maps and produce ad-hoc cutouts for further processing. And, finally, SPACE-ML automates the identification and classification of compact and extended radio sources, employing state of the art Machine Learning and Deep Learning techniques. NEANIAS outcomes will significantly contribute to materialize the Open Science paradigm, enforcing easier software portability, knowledge sharing and result reproducibility, which are three fundamental requirements to successfully exploit radio astronomical data in the SKA era.

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