Observing the radio sky with **PICTOR**

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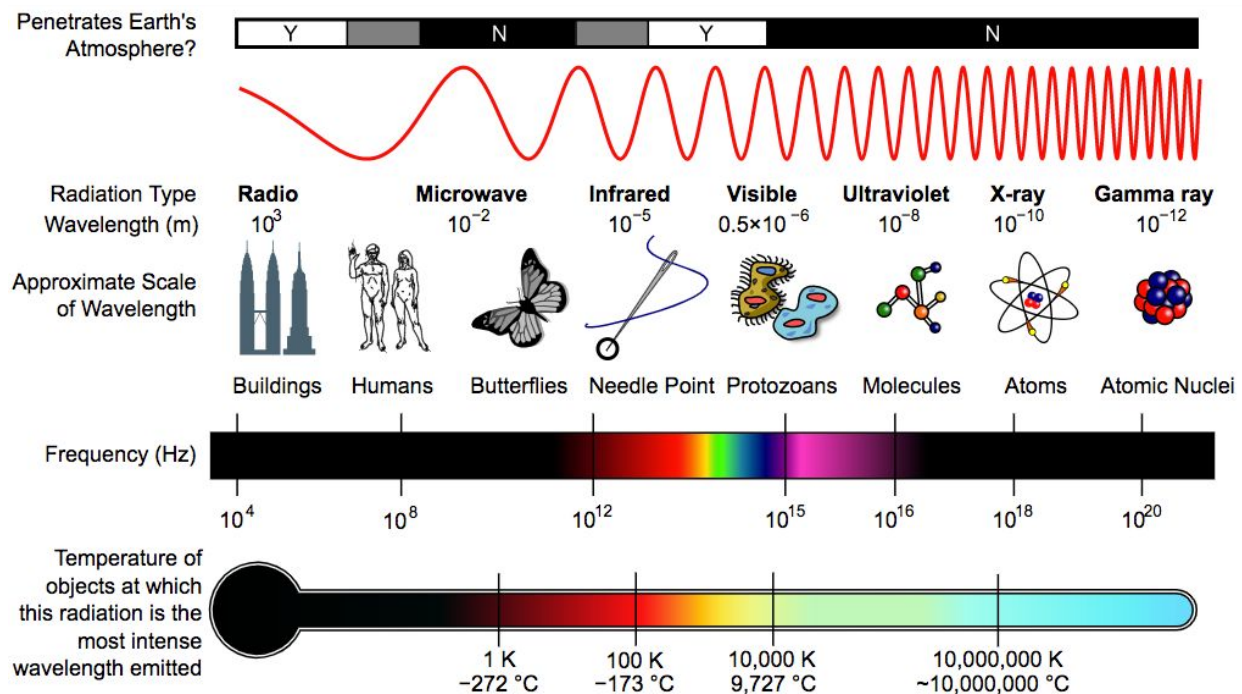
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Introduction: What is radio astronomy?

Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies. Unlike traditional telescopes that observe the sky in the visible part of the electromagnetic spectrum (**400-700 nm**), radio telescopes observe the sky in wavelengths **ranging from centimeters to a few meters**.
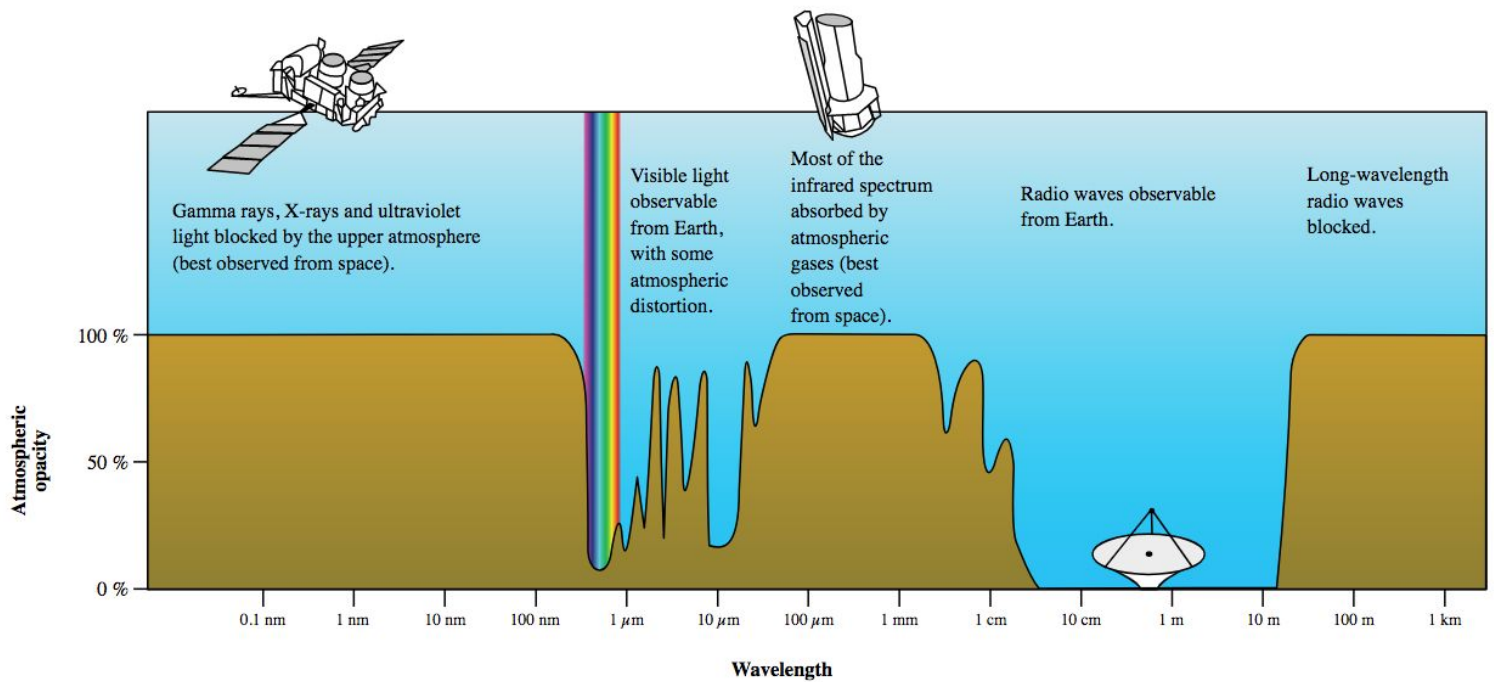

Fig. 1: A diagram of the electromagnetic spectrum, showing various properties across the range of frequencies and wavelengths.

But why should we observe in radio wavelengths?

There are several reasons to observe the sky at radio frequencies. The most common reason radio astronomers point radio telescopes to the sky is **to study sources that produce radio emissions**: radiation that is invisible to the human eye, but is capable of providing compelling information to astronomers & astrophysicists.

A significant advantage radio astronomers have over IR, UV and high-energy astronomers is the atmospheric window: **our atmosphere is completely transparent to radio waves**, so we don't need to send large radio antennas to space (like we usually have to do with IR/UV/high-energy astronomy satellites) in order to efficiently expose our instruments to the sky.

Fig. 2: A diagram showing the amount of absorption of each wavelength of light by the Earth's atmosphere, highlighting the atmospheric windows.

It is also worth noting that radio observations can be carried out **during both daytime and nighttime**, and even under poor weather conditions (e.g. clouds)!

Last but not least, we can utilize the techniques of radio interferometry and aperture synthesis using large arrays of antennas **to achieve extremely high (angular) resolution observations**, which is how the first image of a black hole became possible (the combination of several radio telescopes around the world allowed the Event Horizon Telescope team to create a virtual telescope the size of the Earth)!

Fig. 3: The Very Large Array (VLA) is one of the most sophisticated radio telescope arrays in the world, consisting of twenty-seven 25-meter radio antennas that can function as a high-resolution radio interferometer.

So... What can I observe with a radio telescope?

There are plenty of sources in the sky that present radio emissions, including **galaxies, supernova remnants, nebulae, radio galaxies, quasars, pulsars, masers and more**. Since the radio telescope you'll be using is primarily used to detect the neutral hydrogen concentration of the spiral arms of the galaxy, we will focus our attention on the hydrogen line.

The 21-centimeter hydrogen line

The **hydrogen line** refers to the electromagnetic radiation spectral line that is created by a change in the energy state of neutral hydrogen atoms. This electromagnetic radiation is at the

approximate frequency of <u>1420.4 MHz</u>, which is equivalent to the wavelength of approximately <u>21 cm</u> ($\lambda = \frac{c}{\nu}$). This wavelength falls within the radio region of the electromagnetic spectrum, and it is frequently observed by radio astronomers. The exact mechanism under which hydrogen atoms emit electromagnetic radiation with a wavelength of 21 cm is slightly complicated, but it's not important if you just wish to perform neutral hydrogen observations (if you're interested to learn how hydrogen atoms can emit radiation, take a look <u>here</u> and <u>here</u>).

About PICTOR

PICTOR is an open-source radio telescope that allows <u>anyone</u> to observe the radio sky using its convenient web platform <u>for free</u>. The goal of this effort is **to introduce students, educators, astronomers and others to the majesty of the radio sky,** <u>promoting radio astronomy education</u>, without the need of building a large and expensive radio telescope.

Observing with PICTOR

In order to observe with PICTOR, you'll just need to follow these steps:

1. Visit <u>https://pictortelescope.com/</u>, click **'Observe'** ➜ click **'Observe'**. Alternatively, just visit <u>https://pictortelescope.com/observe</u> directly.
2. You should see a form that allows you to input certain parameters for your observation (refer to the following section to learn what parameters should be used for a successful observation). Once you fill those in, click **'Submit'**.
3. Wait for PICTOR to finish observing the sky. The duration of the observation depends on the duration you specified (+ 1 to 2 minutes for the observation to begin etc.). Once the observation is complete, the data will be delivered to your email as an image attachment.

Parameters and their meaning

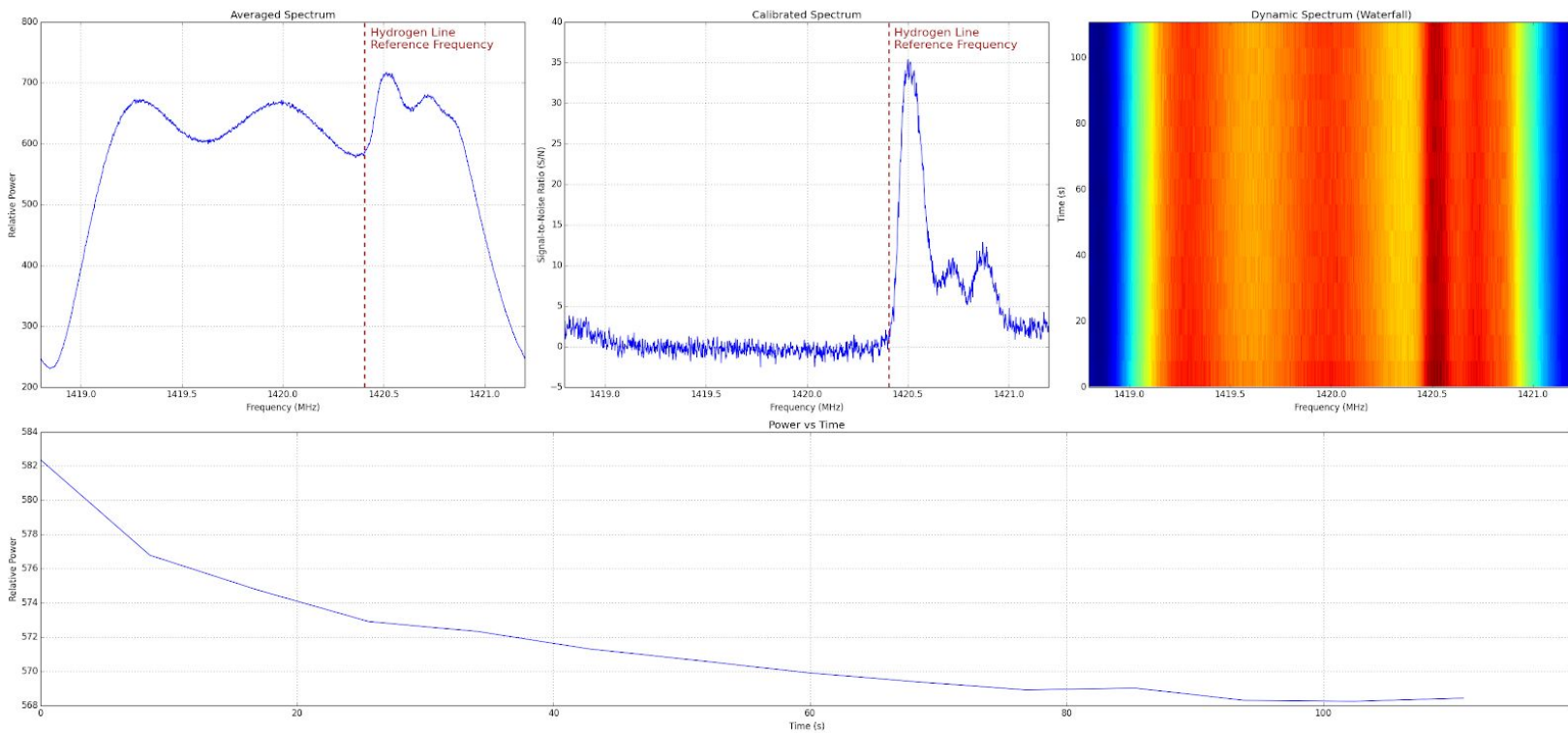| Parameter	Meaning	Example value
Observation name	A name for your observation	My first HI observation
Center frequency (MHz)	The frequency you wish to observe at	1420
Bandwidth	The frequency range you wish to (simultaneously) observe	2.4 MHz
Number of channels	The amount of data points on the frequency axis (more channels = higher frequency resolution)	2048
Number of bins	This allows you to affect the duration of each sample* (similar to exposure time in photography)	10000
Duration	The duration of your observation	300
Email	The email address the data should be delivered to	email@example.com

*Each sample lasts $T_{int} = \frac{n_{bins} \times n_{chan}}{bandwidth}$, where T_{int} is the integration time in seconds, n_{bins} is the number of bins, n_{chan} is the number of channels and $bandwidth$ is the instantaneous bandwidth in Hz.

When is the best time to observe the hydrogen line?

The most "ideal" time to observe and detect the 21 cm line would be **when the Milky Way plane is in the telescope's beam* (field of view)**. To check when the galactic plane is directly overhead (the telescope constantly points to the local zenith), you can use a free planetarium software like Stellarium (set the location to **'National Observatory of Athens'** (any location in Athens should give precise-enough results)).

*The beamwidth of the telescope is 8.95°, so imagine a circle with an angular diameter of 8.95° centered at zenith being your "field of view" (beyond that, the sensitivity of the antenna becomes insignificant).

The following figure is a 2-minute observation with PICTOR (when the galactic plane is _in the beam_):

Fig. 4: Example observation. Top left: Averaged Spectrum, top center: Calibrated Spectrum, top right: Dynamic Spectrum (Waterfall), bottom: Time series (Power vs Time plot).

The top left plot is the **averaged spectrum**, showing the average power (intensity) for every frequency. The top center plot is the **calibrated spectrum**, which is identical to the averaged spectrum, with the effects of the receiver removed (so the noise floor becomes flat and the peaks become more distinct). The top right plot shows the **dynamic spectrum (waterfall)** (a Power vs Frequency vs Time graph displayed as a 2D plot with a colormap indicating Power) and the bottom plot shows the average power vs time plot. The **calibrated spectrum** plot is usually sufficient for beginner observers.

We see three curvy bumps in the averaged spectrum. This is due to the receiver's bandpass shape (different sensitivity at each frequency) and **should _not_ be mistaken for radio emissions** (this is why we should refer to the **calibrated spectrum**: to account for the receiver's instabilities, imperfections, effects etc.).

As you can see, **there are three distinct peaks** on the calibrated spectrum <u>at around 1420.5, 1420.7 and 1420.85 MHz</u>. This is the hydrogen line, and it's **blueshifted** (frequency > 1420.4 MHz), **meaning the source is approaching us**! <u>We've just detected 3 unique spiral arm of our own galaxy</u>, and by conducting another observation (i.e. when the other side of the Milky Way is in the beam), we should expect to see differently Doppler-shifted line(s), potentially indicating more spiral arms, Doppler-shifted (redshifted or blueshifted) to a different degree. From a 2-minute observation with PICTOR, we've just proven that beyond any doubt, **we do indeed live in a spiral galaxy**!

Using a few simple Doppler shift equations you are also encouraged to find the velocity of the detected spiral arms relative to Earth.

Conclusion

I hope this instrument introduces you to the majesty of the radio sky and encourages you to observe the sky in radio wavelengths. If you'd like to learn more about radio astronomy, the following resources are highly recommended:

- Mapping the Galaxy with Radio Astronomy: https://youtu.be/-UrzmAa62ho
- Radio Astronomy in Five Minutes: https://youtu.be/3EcrrLNlWdE
- National Radio Astronomy Observatory (NRAO): https://public.nrao.edu/radio-astronomy/
- The Hydrogen 21-cm Line: http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html
- What is Radio Astronomy - ATNF: https://www.atnf.csiro.au/outreach/education/everyone/radio-astronomy/index.html

If you have any questions, feedback, suggestions or anything else you'd like to contact the author about, feel free to email me at 0xcoto@protonmail.com and I'll be happy to get back to you shortly!

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