ASTR469 Lecture 15: Radio Astronomy

Assess yourself/study guide after lecture & reading (without peeking at notes)...

1. Remind yourself: what defines the field of view and the resolution of an interferometer?

2. What telescope has a larger field of view: the 64 m-diameter Parkes telescope or the 20 m-diameter outreach antenna in Green Bank?

3. What telescope can collect the greater number of photons per second: the 100 m-diameter Green Bank Telescope or ATCA, which consists of six antennae of 22 m-diameter each?

4. For a cross-dipolar telescope with $G = 0.7\,\mathrm{K/Jy}$ and a receiver cooled such that $T_{\mathrm{sys}} = 30\,\mathrm{K}$, what is your limiting sensitivity for a 1-minute observation with $\Delta\nu = 1\,\mathrm{GHz}$? The limiting sensitivity is typically given by a signal that is three times the noise in an observation.

1 Radio Astronomy

The radio regime goes from $\sim$ 10 MHz to $\sim$ 1 THz ($\sim$ 30 m to 0.3 mm). The lower bound is caused by our ionosphere, which is opaque to lower frequencies, and the upper bound is a more-or-less arbitrary boundary with the infrared. It spans 5 decades or frequency-space, which is larger than any other wavelength regime.

Within the radio regime, we can observe at basically any frequency from the ground. At the upper end, the atmosphere (primarily water vapor) can make observing very difficult. As with optical, cold and clear are the best, at high elevation to get above the water vapor. Night time may be necessary for high frequency radio, which is more temperature sensitive. At the lower end, we can observe through snow.

One could spend an entire graduate career learning the ins and outs of radio astronomy, but here I'd like to give you a general sense of how radio astronomical observations work and a few "critical basics" in planning observations and making measurements.

2 A brief history of local relevance

Karl Jansky detected the first radio signal of extraterrestrial origin. We can see a replica of his antenna when we take our trip to Green Bank.

Since the signal peaked about every 24 hours, Jansky originally suspected the source of the interference was the Sun crossing the view of his directional antenna. Continued analysis showed that the source was not following the 24 hour daily cycle of the Sun exactly, but instead repeating on a cycle of 23 hours and 56 minutes, the exact length of a sidereal day, the timing you would get if the source was an astronomical one, "fixed" in relationship to the stars and passing in front of the antenna once every Earth rotation.

Grote Reber was inspired by Jansky's work, and built a parabolic radio 9m in diameter in his own backyard in Illinois, in 1937. He began by repeating Jansky's observations, and went on to conduct the first sky survey in the radio frequencies. A number of years ago they actually shipped his actual telescope from his backyard to Green Bank, so we will also see his antenna there!

3 Basics of radio telescopes

Radio telescopes come in many shapes and sizes, but **the most fundamental part all radio telescopes is the "dipole"**, which is an unshielded stretch of wire or metal that is conductive, and hence reacts to radio waves. When a radio wavefront is incident on a dipole antenna, it induces sinusoidal oscillations of electrons in the wire, i.e. it induces a current. This current is detected as a voltage variation. While the wire will detect many different waves, all of the information about their frequency, amplitude, and phase is maintained in the voltage variations. The resulting radio signal is then carried down a cable and amplified, sometimes filtered or altered in various ways, then digitized. Radio astronomers analyze the resulting digitized signal in various ways.

Typically radio receivers use a 'crossed dipole,' which is two dipoles in an orthogonal orientation. This allows the combined signal from those two dipole antennae to collect all polarization information about a target source.

Radiometer is the term used to describe the signal chain starting from the dipole and ending just before the digitizer.

The rest of many radio telescopes include one or more of the following parts:

- **A primary reflecting surface**, which acts to collect more light and focus it onto your dipole. Sometimes there are secondary surfaces as well to redirect the light collected by the primary surface. As with the optical regime, this is your man "collecting area" for photons, and is defined by the surface area of the primary aperture. Most primary surfaces (mirrors/dishes) in radio astronomy are spheroid or paraboloid surfaces. The radio regime is diffraction-limited so we get a resolution set by the Rayleigh criterion for a *single dish* that is defined by the primary dish diameter (assuming the aperture is roughly circlar):
$$\theta \simeq \frac{\lambda}{D} \tag{1}$$
In the specific case of radio astronomy, this defines both the resolution and the field of view of the telescope. Essentially a single crossed dipole is a one-pixel camera (in radio, we say it has one "beam").

- **A waveguide** or a "feed horn" or a "feed" (these are different words for the same object) is sometimes used to filter out specific wavelengths into the dipole, which sits at the base of the feed.

- **The backend** is what ultimately processes the data or perhaps filters it in some way. This can be a correlator (to compare signals from multiple dishes), a spectrometer (which will produce a spectrum), or a continuum backend (which gives the total intensity) or specialized pulsar backends. For now we'll just say these are black boxes of electronics. The backend has a particular bandpass over which it can collect data, and a certain number of "channels" for spectra line data. These can be configured depending on your requirements.

3.1 Side note: interferometry

One of the key points of our above discussion of dipoles is that here we are treating waves like *waves* instead of *photons*, like we did in optical-band detection with CCDs. One key point is that we track the phase of radio waves, which allows us to do interferometry. In interferometry, we correlate the voltage signals from multiple dishes, with the signal from one dish corrected for the additional travel time (the delay) that it takes the wave front to get between the first and second antenna.

In interferometry, the antennae are spaced in different locations. What's great is that as far as resolution is concerned, the effective diameter of the interferometer is equal to the longest baseline.[1] This, the resolution of an interferometer is:

$$\theta \simeq \frac{\lambda}{B} \tag{2}$$

where B is the longest separation between two antennae. Note that the field of view of an interferometer is still given by the field of view of the largest dish in the array (as given above for a single dish).

4 Radio light and radio noise

4.1 Brightness temperature

When quantifying radio light, one simplification we often use is to treat all radio sources and all noise sources as thermal (blackbody) emitters:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} \simeq \frac{2h\nu^3}{c^2}\frac{kT}{h\nu} = \frac{2\nu^2}{c^2}kT \tag{3}$$

This, if you recall, is the Rayleigh-Jeans limit. It makes our lives much much easier. Since B and T are directly proportional, we often work in terms of "temperature" T. Here we define the **brightness temperature** of a radio source to be:

$$T_{\rm B} \equiv \frac{c^2 B_\nu}{2k\nu^2} \tag{4}$$

Note that:

- If the emitter is a blackbody, $T_{\rm B}$ is the actual temperature of the object.
- If the emitter is *not* a blackbody (like a pulsar, synchrotron source, etc as described below), then this dos not represent a physical temperature. Instead it represents the observed brightness of the source at that particular frequency, which as previously noted represents a voltage induced in the electronics.

4.2 Radiometer noise

We define brightness temperature for convenience. Many different sources of radio-wave emission contribute noise to an observation. This includes self-noise from the source (typically not blackbody, but represented by brightness temperature T_{src}), sky/background noise from e.g. our own galaxy (T_{sky}), noise from the atmosphere (T_{atm}), actual thermal noise from the receiver itself (T_{rec}, usually cooled to a few tens of Kelvin), and noise from the cosmic

[1] This is true for resolution only; the total collecting area of an interferometer just the sum of the collecting areas of all the individual dishes.

microwave background (T_{cmb}). These all enter as inducing noise into the observation and do so additively:

$$T_{\text{noise}} = T_{src} + T_{atm} + T_{rec} + T_{sky} + T_{cmb} + ... \tag{5}$$

...plus any other noise sources being detected by the dipole (those listed above are the primary ones).

The measurement noise in an observation is then given as

$$\sigma_{\text{T}} = \frac{\text{mean temp}}{\sqrt{\text{\# independent samples}}} = \frac{T_{\text{noise}}}{\sqrt{n_p \Delta\nu t}} \tag{6}$$

This is known as the "radiometer equation," and gives the noise measurement in the data. The n_p term is the number of polarization measurements (1 for a single dipole, 2 for a crossed dipole), $\Delta\nu$ is the bandwidth of your observation, and t is the total integration time. Importantly, this gives the radiometer noise; it does not tell you about signal amplification and thus does not explicitly give you flux; see the next section for the relevant expression.

4.3 Measuring the signal and S/N

The signal just as in our photometry lecture, comes from the source itself (but this time it's the source brightness temperature, T_{src}). However, typically we want to measure an actual source flux (or predict what S/N we should get given a particular flux). So, let's translate this brightness temperature to a flux. Just like the specific intensity before, we can integrate the antenna temperature over the extent of a source of solid angle Ω:

$$F = \int B_\nu(T) d\Omega = \int \frac{2\nu^2}{c^2} kT d\Omega \tag{7}$$

which in the case of a uniform brightness gives

$$F = \frac{2\nu^2}{c^2} kT\Omega \tag{8}$$

Radio signals are incredibly weak. Radio signals are quite weak. We typically use a unit called a Jansky, which converts as $1\,\text{Jy} = 10^{-26}\,\text{W}\,\text{m}^{-2}\,\text{Hz}^{-1}$.

Note that the full expression for the S/N in flux form is a commonly used sensitivity measure:

$$\frac{\text{S}}{\text{N}} = F_\nu \frac{G\sqrt{n_p t \Delta\nu}}{T_{\text{sys}}} \tag{9}$$

Here, F_ν is the flux of your target source. The factors under the square root are the same as previously described; within the bounds of your telescope's capabilities, those are the factors that you can typically define in an observation. The ones set strictly by the antenna itself are G and T_{sys}. When you go to observe with any professional radio telescope system, these will usually be given as an estimation for what the noise and sensitivity characteristics of the antenna are. G is the antenna "gain," with units of K/Jy. This can account for the additional collection surface if you're using a large reflecting dish to collect signal into your dipole(s). T_{sys} is the system temperature, which quotes the T_{noise} given above but without considering your actual target source (it only characterizes other sources of antenna and sometimes sky noise).

5 What makes radio signals?

The main thing that makes radio signals is free electrons. Any acceleration of a charged particle, like an electron, makes photons. I've previously noted that the sky brightness in the radio regime is dominated by radio sources that are not actually blackbody emitters. Instead there are a few other emission mechanisms that give rise to bright radio waves:

- **Synchrotron emission**. This occurs when relativistic electrons are incident on a magnetic field. An electron in a magnetic field begins to spiral, and synchrotron emission is the emission that comes out as a result of that spiraling motion. Synchrotron emission typically peaks at low radio frequencies. This is common in a few types of sources:
    - Active galactic nuclei, where electrons are jetted relativistically from a supermassive black hole in a collimated flow into the surrounded medium.
    - Shock waves (as in supernova remnants or giant radio lobes at the end of radio jets), which are charged particles ramming into an ambient plasma.
    - Ambient cosmic rays (charged electrons from distant sources) that are travelling through the diffuse magnetic field in our galaxy.
- **Thermal Bremsstrahlung (free-free emission)** arises from an ionized cloud, and occurs when a free electron passes by an ion, and changes direction due to that encounter. That change in direction is an acceleration, and causes emission which is peaked at radio wavelengths. The most prominent source of thermal bremsstrahlung is HII regions that reside in star-forming regions around young stars.
- **Spectral lines** we have previously spoken about. Many of these occur at radio wavelengths, and most prominently the HI line.
- **Pulsars** have emission that is brighter at low radio frequencies, and whose physical emission process is not fully understood.
- **Blackbody emission** does occur in the radio. Most prominently it comes from the cosmic microwave background, and from the Sun. Most other blackbody sources are too faint and too far to see compared to the other above-listed mechanisms.