What is “seeing”?

• We “see” an object when the electromagnetic radiation it emits or reflects interacts with cells in our eyes.

• Astronomers “see” an object when the electromagnetic radiation it emits or reflects interacts with our detectors.
So what is electromagnetic radiation?

- A traveling, massless packet of energy which corresponds to an oscillating electric and magnetic field
  - Also known as: radiation, or a light wave, or a photon

Travels at the speed of light (by definition).

Remarkably, all radiation travels at this speed, regardless of whether it carries a lot of energy or only a little.
The nature of the radiation is described by its wavelength and/or frequency and/or energy.

Distance between peaks = wavelength, \( \lambda \)

Number of peaks that past by each second = frequency, \( \nu \)

\[
\lambda = \frac{\text{speed of light}}{\nu}
\]

Long wavelengths = short frequencies
Short wavelengths = high frequencies
The Electromagnetic Spectrum

Wavelength range: 300 meters to 0.5 mm
Frequency range: 1 MHz (1 million Hertz or cycles per second) to 500 GHz (500 billion Hertz)

Longer waves
Lower energy
Lower frequency

Shorter waves
Higher energy
Higher frequency
The one idea I want you to take home with you:

We do not “listen” to Radio Data
Radio Waves are not Sound Waves

- Radio waves are electromagnetic radiation, exactly like light (and x-rays, and microwaves, etc).
- Sound waves are pressure waves. Require a medium (air, water, etc.) to travel through.
- Sound is created by a pressure wave moving a membrane in your ear. Your brain turns the vibration of this membrane into “sound”.

![Diagram showing the ear, medium, and sound]
You do not listen to radio waves with a radio

Sound wave
5 Hz – 20 kHz

Microphone membrane

Electronically encoded sound wave (5 Hz – 20 kHz)

Electronically Modulated

Radio wave
At broadcast frequency (e.g., 1100 kHz)

Modulated signal =

Radio signal modulated by electronically encoded sound

Your radio, tuned to the appropriate frequency: de-modulates broadcast frequency; electronically encoded sound wave drives speaker cone

Radio broadcast tower
Radio Telescopes

• Come in two basic flavors:

Green Bank Telescope, WV

Very Large Array, NM

Single Dish

Arrays
Robert C. Byrd Green Bank Telescope

- 2000 dedication
- Operated from West Virginia
- 100 x 110m, novel offset design
- Just coming into full operation
The Very Large Array (VLA)

- 1980 dedication
- Twenty-seven 25-m antennas in reconfigurable array outside of Socorro, NM
- Has produced more published science than any other telescope on the face of the Earth
Very Long Baseline Array (VLBA)

- 1993 dedication
- Operated from Socorro
- Ten 25-m antennas spread across US, Canada, P.R.
- Highest resolution imager in astronomy
Other Millimeter & Centimeter Wave Radio Telescopes

Arecibo, P.R.

Owens Valley Radio Observatory, CA

Berkeley-Illinois-Maryland Array, CA
Radio Telescopes: Resolution

- Resolving power (how small of a thing you can “see”) depends on the size of the telescope and the wavelength of the light.

\[
\lambda \quad \text{size}
\]

For radio waves, this is large...

So this must also be large.

- “Size” = diameter of telescope for single dish; maximum distance between telescopes for arrays.
Radio Telescopes: Resolution

Single Dish | Arrays
Reconfigurable Arrays: Zoom Lens Effect

• Larger arrays give you better and better resolution
• Trade-off with sensitivity (collecting area stays the same while diameter increases)
Radio Telescopes: Sensitivity

- Sensitivity (how faint of a thing you can “see”) depends on how much of the area of the telescope/array is actually collecting data
  - VLA B-array: Total telescope collecting area is only 0.02% of land area
- More spread-out arrays can only image very bright, compact sources
Basic Elements of a Radio Antenna

VLBA Antenna:
- 25 meters (82 feet) in diameter
- As tall as a 10-story building
- Weighs 240 tons
- Aluminum reflecting surface
- Focuses incoming waves to prime focus or sub-reflector
Sub-reflector

- Re-directs incoming waves to Feed Pedestal
- Can be rotated to redirect radiation to a number of different receivers
Feed Pedestal

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5GHz</td>
<td>20cm</td>
</tr>
<tr>
<td>2.3GHz</td>
<td>13cm</td>
</tr>
<tr>
<td>4.8GHz</td>
<td>6cm</td>
</tr>
<tr>
<td>8.4GHz</td>
<td>4cm</td>
</tr>
<tr>
<td>14GHz</td>
<td>2cm</td>
</tr>
<tr>
<td>23GHz</td>
<td>1.3cm</td>
</tr>
<tr>
<td>43GHz</td>
<td>7mm</td>
</tr>
<tr>
<td>86GHz</td>
<td>3mm</td>
</tr>
<tr>
<td>327MHz</td>
<td>90cm</td>
</tr>
<tr>
<td>610MHz</td>
<td>50cm</td>
</tr>
</tbody>
</table>
Antenna Feed and Receivers
Benefits of Observing in the Radio

- Track physical processes with no signature at other wavelengths
- Radio waves can travel through dusty regions
- Can provide information on magnetic field strength and orientation
- Can provide information on line-of-sight velocities
- Daytime observing (for cm-scale wavelengths anyway)
Primary Astrophysical Processes Emitting Radio Radiation

When charged particles change direction, they emit radiation

- **Synchrotron Radiation**
  - Charged particles moving along magnetic field lines

- **Thermal emission**
  - Cool bodies
  - Charged particles in a plasma moving around

- **Spectral Line emission**
  - Discrete transitions in atoms and molecules
Synchrotron Radiation

Synchrotron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field.

- Polarization properties of light provides information on magnetic field geometry
Thermal Emission

- Emission from warm bodies
  - “Blackbody” radiation
  - Bodies with temperatures of ~ 3-30 K emit in the mm & submm bands

- Emission from accelerating charged particles
  - “Bremsstrahlung” or free-free emission from ionized plasmas
Spectral Line emission: hyperfine transition of neutral Hydrogen

Lower energy state: Proton and electron have opposite spins.

Emits photon with a wavelength of 21 cm (frequency of 1.42 GHz)

Transition probability $= 3 \times 10^{-15} \text{ s}^{-1} = \text{once in 11 Myr}$
Spectral Line emission: molecular rotational and vibrational modes

- Commonly observed molecules in space:
  - Carbon Monoxide (CO)
  - Water (H₂O), OH, HCN, HCO⁺, CS
  - Ammonia (NH₃), Formaldehyde (H₂CO)
- Less common molecules:
  - Sugar, Alcohol, Antifreeze (Ethylene Glycol), ...

malondialdehyde
Spectral Line Doppler effect

- Spectral lines have fixed and very well determined frequencies
- The frequency of a source will change when it moves towards or away from you
- Comparing observed frequency to known frequency tells you the velocity of the source towards or away from you
Special example of Spectral Line observation: Doppler Radar Imaging

Transmit radio wave with well defined frequency...

..observe same frequency

...bounce off object...

NASA’s Goldstone Solar System Radar

Very Large Array
Brief Tour of the Radio Universe

- Solar System
  - Sun, Planets, Asteroids

- Galactic objects
  - Dark clouds, proto-stellar disks, supernova remnants,

- Galaxies
  - Magnetic fields, neutral hydrogen

- Radio Jets

- The Universe
Our Star, The Sun

- Radio Sun
- Coronal Mass Ejections (CMEs)
- “Space weather”
- Structure of Solar Wind

Courtesy Steven White (UMd)
Thermal free-free emission from chromosphere and active regions.
Dark filaments=dense cool material suspended in the corona
Solar Magnetic Field Strength and Structure

Active region showing strong shear: radio images show high $B$ and very high temperatures

from Lee et al (1998)
Solar Flares

Type U bursts observed by Phoenix/ETH and the VLA.

Aschwanden et al. 1992
Coronal Mass Ejections (CMEs)

- Largest explosions on the Sun
- Large portion of the Solar Corona destabilizes and is ejected at speeds of 200-2000 km/s
- Accelerate charged particles to close to the speed of light
- Major drivers of “space weather” effects
  - Can take down power grids, induce currents in oil pipelines, disrupt navigation

[Image: Optical light SOHO/LASCO]

cdaw.gsfc.nasa.gov/CME_list/
Synchrotron Radiation from MeV electrons. $B \sim 1$ Gauss

Bastian et al. (2001)
Particles accelerated during Solar Flares and CMEs can seriously impact interplanetary travel.
Venus

- Optical/UV view of Venus from Pioneer 10
  - Clouds, clouds, and more clouds
- 13 cm Radar image of Venus using Arecibo and GBT
  - Bright=rougher surface
  - Dark=smoother surface

Campbell, Margot, Carter & Campbell
Jupiter
Charged particles trapped in Jupiter's magnetic field
Similar to Earth's Van Allen belt

At times, Jupiter outshines the Sun at radio wavelengths – can use this fact for finding extrasolar analogs

Observations: VLA 20 cm
De Pater, Schulz & Brecht 1997


www.atnf.csiro.au/people/rsault/jupiter/movies/
Doppler Radar Imaging of Asteroids

- S-band (2380 MHz, 12.6 cm) radar imaging of main belt Asteroid 216 Kleopatra using Arecibo
- 217 km by 94 km by 81 km
- “dog-bone” structure may be the result of two asteroids colliding
Doppler Radar Imaging of Asteroids

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Computer reconstruction by Ostro et al. 2000, Science, 288, 836 echo.jpl.nasa.gov
Formation of a Star

• In early stages, before star turns on, protostar is enshrouded in gas and dust
• Radio and far-infrared are the only types of radiation which can get out
• Gas cloud contains many trace molecules (CO, NH$_3$, many others) which emit at mm wavelengths
Gas glows most brightly where accretion onto a protostar warms the cloud.

A. Wootten & G. Fuller
www.nrao.edu/imagegallery
Proto-stellar Outflows

“9 point” radio map of bipolar molecular outflow from the S106 protostar
Blue=Towards us
Red=Away from us

S106, IR Subaru Telescope, Japan
G192.16-3.82 – Inner Accretion Disk

VLA + VLBA 43 GHz (7mm) observations of ionized gas and warm dust from inner-most region surrounding massive protostar (Shepherd et al. 2001).

Contours: observations
Color: model of accretion disk, central star, outflow, & companion protostar:
- $8 \, M_{\odot}$ protostar
- $3-20 \, M_{\odot}$ disk
- Outflow with $40^\circ$ opening angle.

Credit: B. Starosta, NRAO/AUI/NSF
• Remnant of a massive star that exploded ~300 years ago
• VLA image at 1.4, 5, and 8.4 GHz
• Synchrotron emission from tangled magnetic fields
The Crab Nebula

- Remnant of a supernovae from 1054 AD
- Expanding at 1000 km/sec
- Central star left behind a rapidly spinning pulsar
- Wind from pulsar energizes the nebula, causing it to emit in the radio

M. Bietenholz
www.nrao.edu/imagegallery
Center of our Galaxy

Wide-Field Radio Image of the Galactic Center
\( \lambda = 90 \text{ cm} \)
(Kassim, LaRose, Lazio, & Hyman 1999)

Credits: Lang, Morris, Roberts, Yusef-Zadeh, Goss, Zhao
Same Space -- Different Light
Extragalactic Supernovae

SN 1993J in M81

VLBA Observation from May 17, 1993 – Feb 25 2000

Bartel, Bietenholz, Rupen et al.

aries.phys.yorku.ca/~bartel/SNmovie.html
Magnetic Field Orientation in Galaxies

Radio Continuum
Beck, Horellou, Neininger

Lines=Magnetic Field Orientation
www.nrao.edu/imagegallery
Neutral Hydrogen in Galaxies

- B/W=optical image of NGC 6946 from Digital Sky Survey
- Blue=Westerbork Synthesis Radio Telescope 21 cm image of Neutral Hydrogen
- Neutral Hydrogen is the raw fuel for all star formation
- Hydrogen usually much more extended than stars
21 cm Spectral Line Observations

Often find things you’d never guess from optical light

Optical Image of Ring Galaxy Arp 143

VLA 21cm observation Appleton et al. 1987
21 cm Spectral Line Observations

Often find things you’d never guess from optical light

VLA 12-pointing mosaic  Yun et al. 1994
Spectral Line Observations also provide velocity information.

This tail is moving away from us.

This tail is moving towards us.


Spatial and Velocity information help motivate physical models.
N-body simulations provide past/future evolution and 3-D geometry

N-body simulation of NGC 4676 “The Mice”
Hibbard & Barnes, in preparation
Information from Radio compliments that from other wavelengths

X-ray: Karovska et al.
Optical: DSS
Radio Continuum: NVSS
21cm: Schiminovich et al.

Chandra.harvard.edu
Radio Jets

An exclusively radio phenomena

200 kpc
650,000 light years

VLA radio (20cm) image
Radio/optical superposition
Optical identification

Optical quasar

Copyright (c) NRAO/AUI 1999

An exclusively radio phenomena
Jet Mechanism:

- Accretion of gas onto a massive central black hole releases tremendous amounts of energy.
- Magnetic field collimates outflow and accelerates particles to close to the speed of light.
VLBA Time-Elapsed Observations of the Innermost Regions of a Jet
AGN Artistic Simulation by Steffen & Gomez
NGC 326: “Smoking Gun” of Colliding Black Holes

- Inset HST optical image shows two nuclei, presumably the result of two galaxies merging.
- “X-shaped radio jets show radi axis has flipped.
- It is thought that only another black hole can realign a black hole jet.

Merritt & Ekers  www.nrao.edu/imagegallery
Wilkinson Microwave Anisotropy Probe (WMAP)

Shepherding in the era of "Precision Cosmology"
So What’s Next for Radio Astronomy?

- **2003-2013:**
  - EVLA: making the VLA ten times better
  - ALMA: VLA for the sub-millimeter
  - ATA: SETI lives on

- **2008-2030+**
  - FASR: solar array
  - LOFAR: low frequency array
  - SKA: collecting area of 75 VLA’s
The VLA Expansion Project: 21st Century Astrophysics with the VLA

EVLA - The Expanded Very Large Array

Built on the infrastructure of the current VLA, including its 27 antennas of 25-meter diameter, the EVLA will incorporate state-of-the-art electronics to replace present equipment dating to the 1970s and may include approximately eight new stations as distant as 250 kilometers from the current array. These features will improve the scientific capabilities of the instrument by a factor of 10 in all key observational parameters.

EVLA - Improved Capabilities

Sensitivity:
Continuum sensitivity improvement by up to a factor of 5 (below 10 GHz) to more than 20 (between 10 and 50 GHz).

Frequency Accessibility:
Operation at any frequency between 1.0 and 50 GHz, and potentially as low as 30 MHz.

Spectral Capabilities:
As many as 262,144 frequency channels will provide flexible, variable resolutions between 1 MHz and 1 Hz.

Spatial Resolution:
Maximum resolution ranging from 0.004 arcsec at 50 GHz to 0.2 arcsec at 1 GHz, complementing the higher resolution of the VLBA.

Implementing the EVLA

The VLA Expansion Project will combine modern technologies with the sound design of the existing VLA to produce a tenfold increase in scientific capabilities for much less than the inflation-adjusted cost of the VLA. The project consists of two phases, with the second phase projected to start midway through implementation of the first phase. The design and development effort for Phase I has now formally begun. A proposal for the Phase II part of the project is currently under development.

Phase I - The Ultrasensitive Array
The Phase I EVLA consists of: wideband receiver systems, a state-of-the-art, flexible correlator, a fiber-optic data transmission system, all new digital electronics, a new powerful on-line control system, and the 27 existing VLA antennas.

Phase II - The New Mexico Array
In Phase II of the EVLA construction, approximately 8 new stations at distances of up to 300 km from the VLA will be brought on-line. The new antennas and some inner VLBA antennas will be connected to the VLA by fiber-optics links.
• ALMA will be an array of 64 precision engineered antennas deployed in the Atacama desert in the high Andes in Chile. Configurable array, like the VLA, to provide a zoom-lens capability.

• Most of the energy in the Universe lies at submillimeter/millimeter wavelengths yet we cannot image the sources of this energy with reasonable detail. ALMA will reach the sensitivity of current submm telescopes in seconds, with resolutions reaching 10mas.

• ALMA has been endorsed as the highest priority project for the next decade by the astronomical communities of the United States, Canada, the United Kingdom, France, the Netherlands and Japan (the latter as LMSA). Planned completion in 2012.
The Allen Telescope Array

- First telescope designed specifically for the Search for Extra-Terrestrial Intelligence (SETI)
- Array of 350 commercial satellite dishes, 6m in diameter. More collecting area than the GBT
- Will speed SETI targeted searching by 100x
  - Will target from 100,000 to 1 million nearby stars
  - Will scan 100 million radio channels
- Start-up scheduled for 2005

www.seti-inst.edu/seti/our_projects
Proposed Radio Instruments:

2008: Low-Frequency Array (LOFAR)
A low-frequency (10-240 MHz) multi-beam-forming array composed of ~100 antenna “stations” each containing ~100 individual antenna, spread over an area of ~400 km. Will open a new window on the Universe.
www.lofar.org

2009: Frequency Agile Solar Radiotelescope (FASR)
A multi-frequency (~0.1 - 30 GHz) imaging array composed of ~100 antennas for imaging the Sun with high spectral, spatial, and temporal resolution.
www.ovsa.njit.edu/fasr/

2030?: Square Kilometer Array (SKA)
A multi-frequency (~0.1 - 3 GHz?) imaging array with a collecting area of 1 square kilometer.
www.skatelescope.org
Conclusions

• Radio astronomical imaging is a relatively young, but rapidly advancing field which will explode in the next decade

• You don’t have to have a well-funded P.R. machine to churn out fascinating science