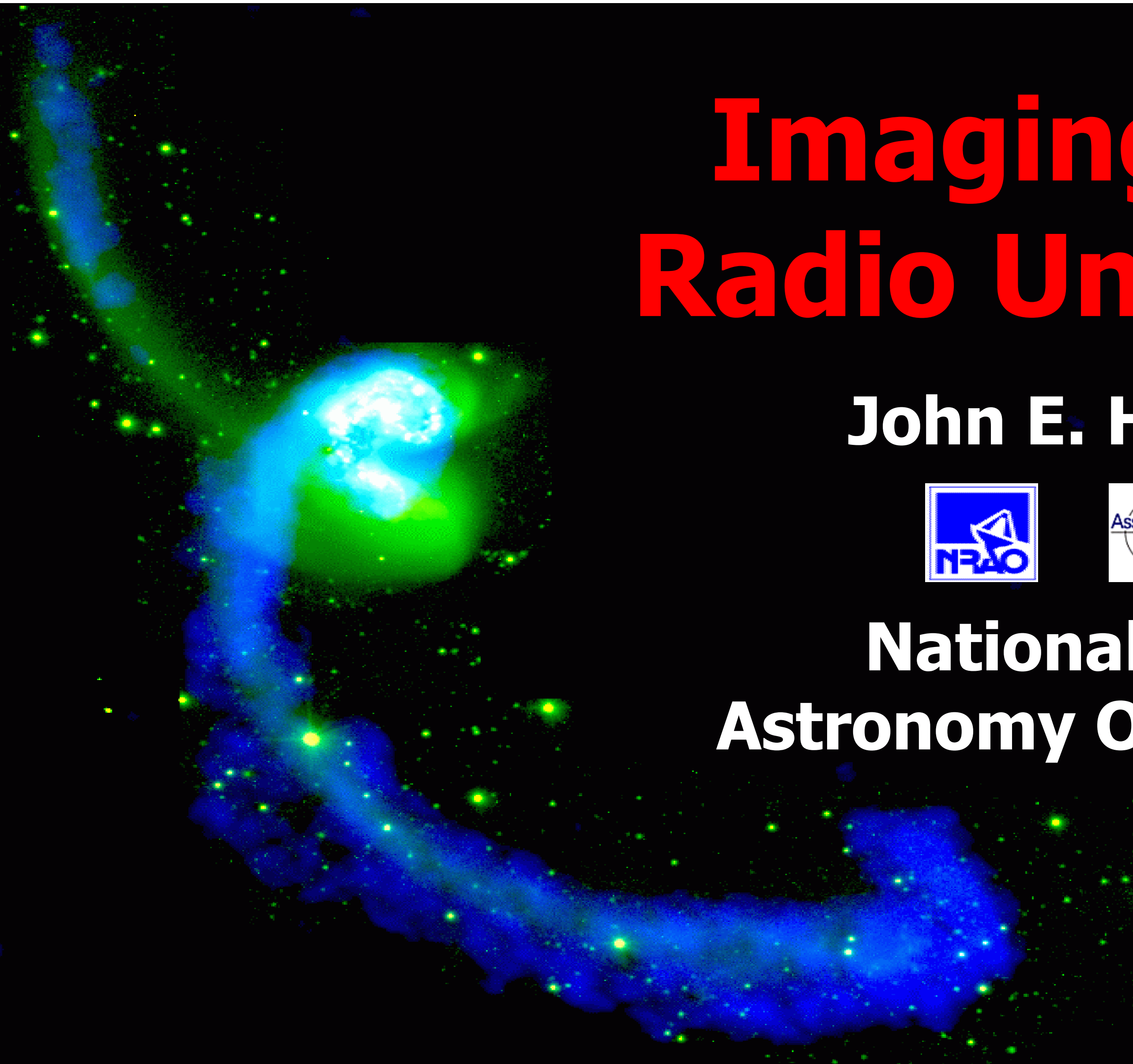
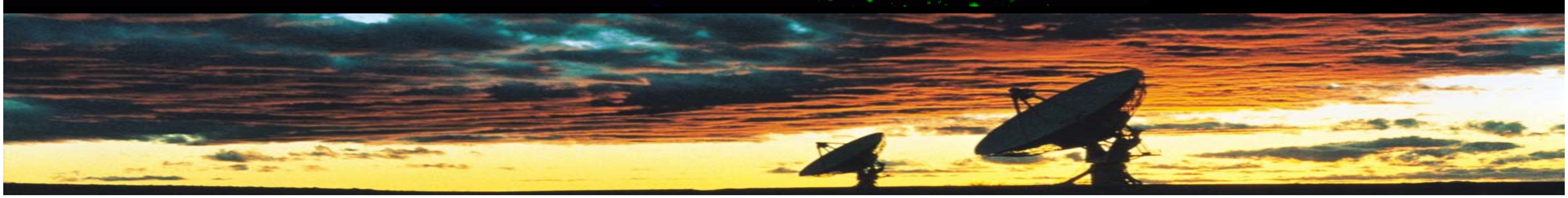
Imaging the Radio Universe



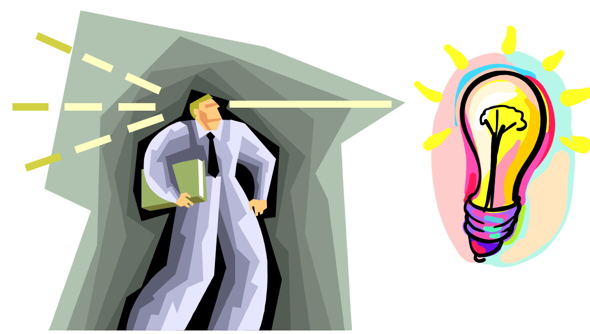
John E. Hibbard

National Radio Astronomy Observatory



What is “seeing”?

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



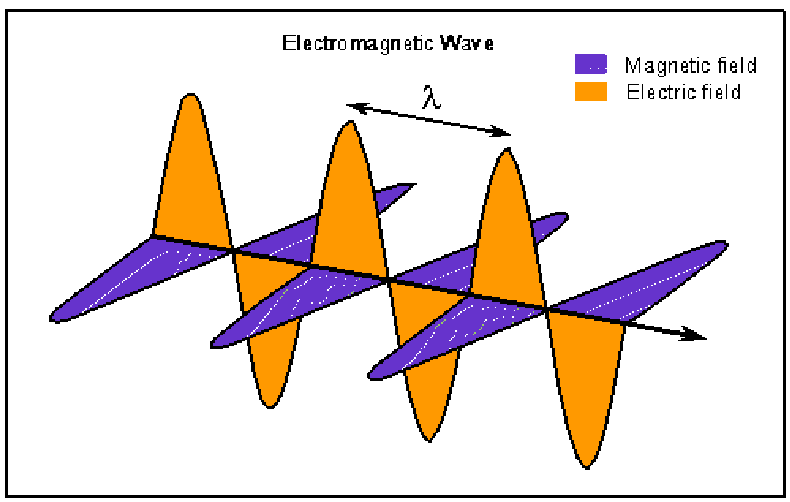
- Astronomers “see” an object when the electromagnetic radiation it emits or reflects interacts with our detectors

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

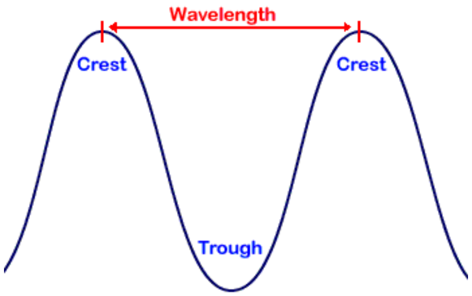
Travels at the speed of light (by definition).

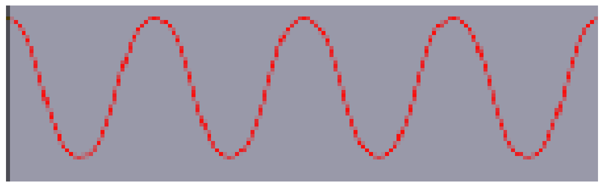
Remarkably, all radiation travels at this speed, regardless of whether is carries a lot of energy or only a little



Animation from Nick Strobel's Astronomy Notes (www.astronomynotes.com)

The nature of the radiation is described by its wavelength and/or frequency and/or energy





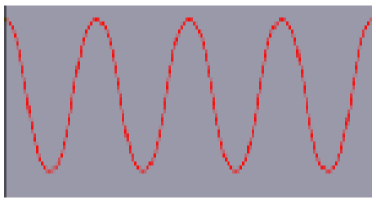
Distance between peaks=wavelength, λ

Number of peaks that past by each second = frequency, ν

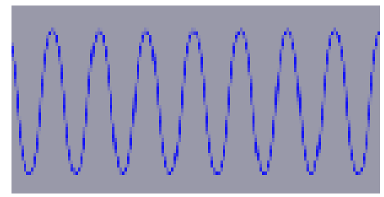
$$\lambda = \frac{\text{speed of light}}{\nu}$$

Long wavelengths = short frequencies
Short wavelengths = high frequencies

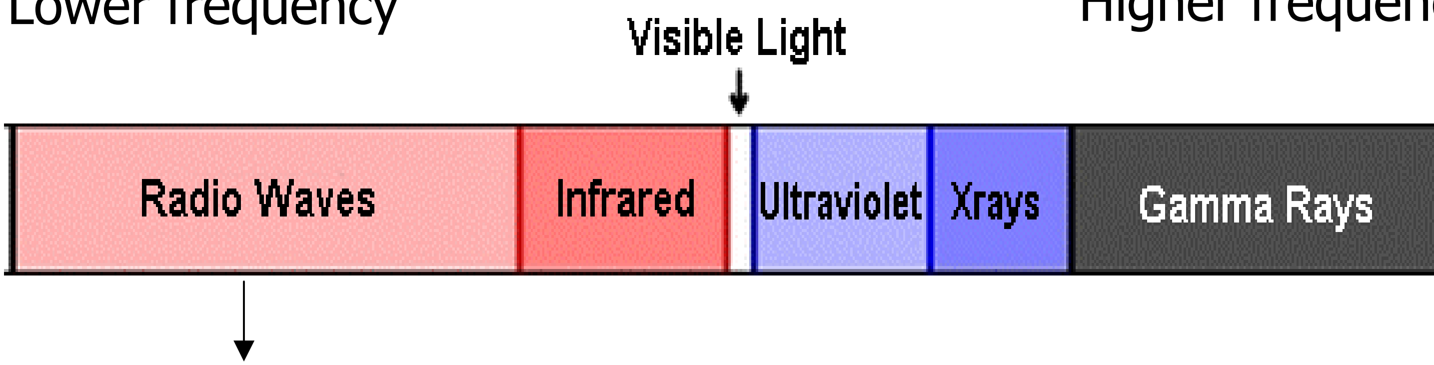
The Electromagnetic Spectrum



Longer waves
Lower energy
Lower frequency



Shorter waves
Higher energy
Higher frequency



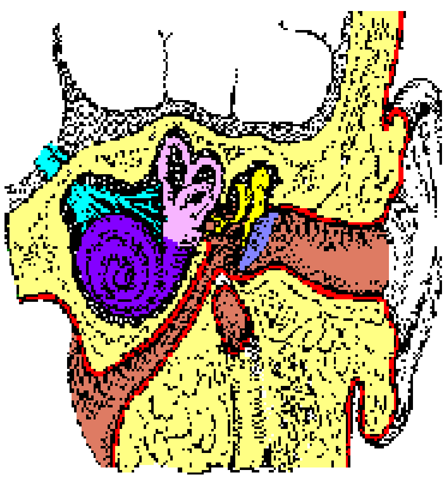
Wavelength range: 300 meters to 0.5 mm
Frequency range: 1 MHz (1 million Hertz or cycles per second) to 500 GHz (500 billion Hertz)

The one idea I want you to take home with you:

We do not “listen” to Radio Data

Radio Waves are not Sound Waves

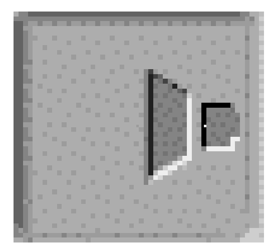
- Radio waves are electromatic radiation, exactly like light (and x-rays, and microwaves, etc).
- Sound waves are pressure waves. Require a medium (air, water, etc.) to travel through.
- Sound is created by a pressure wave moving a membrane in your ear. Your brain turns the vibration of this membrane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



Ear

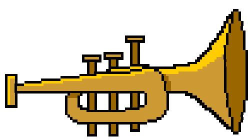
Medium

Sound



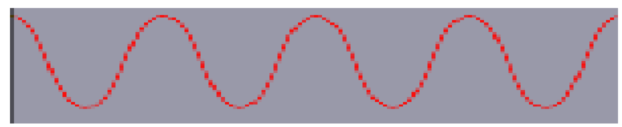
You do not listen to radio waves with a radio

Sound wave
5 Hz – 20 kHz



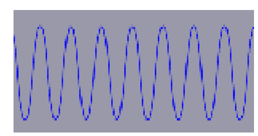
Microphone membrane

Electronically encoded sound wave (5 Hz – 20 kHz)



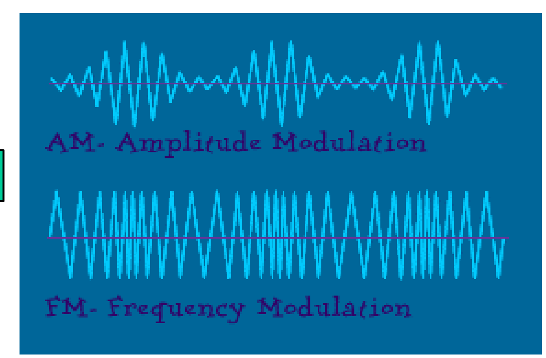
Electronically Modulated

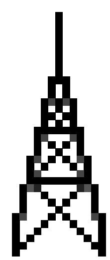
Radio wave
At broadcast frequency
(e.g., 1100 kHz)



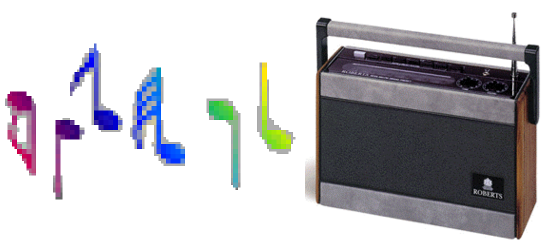
Modulated signal =

Radio signal modulated by electronically encoded sound





Radio broadcast tower



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

Radio Telescopes

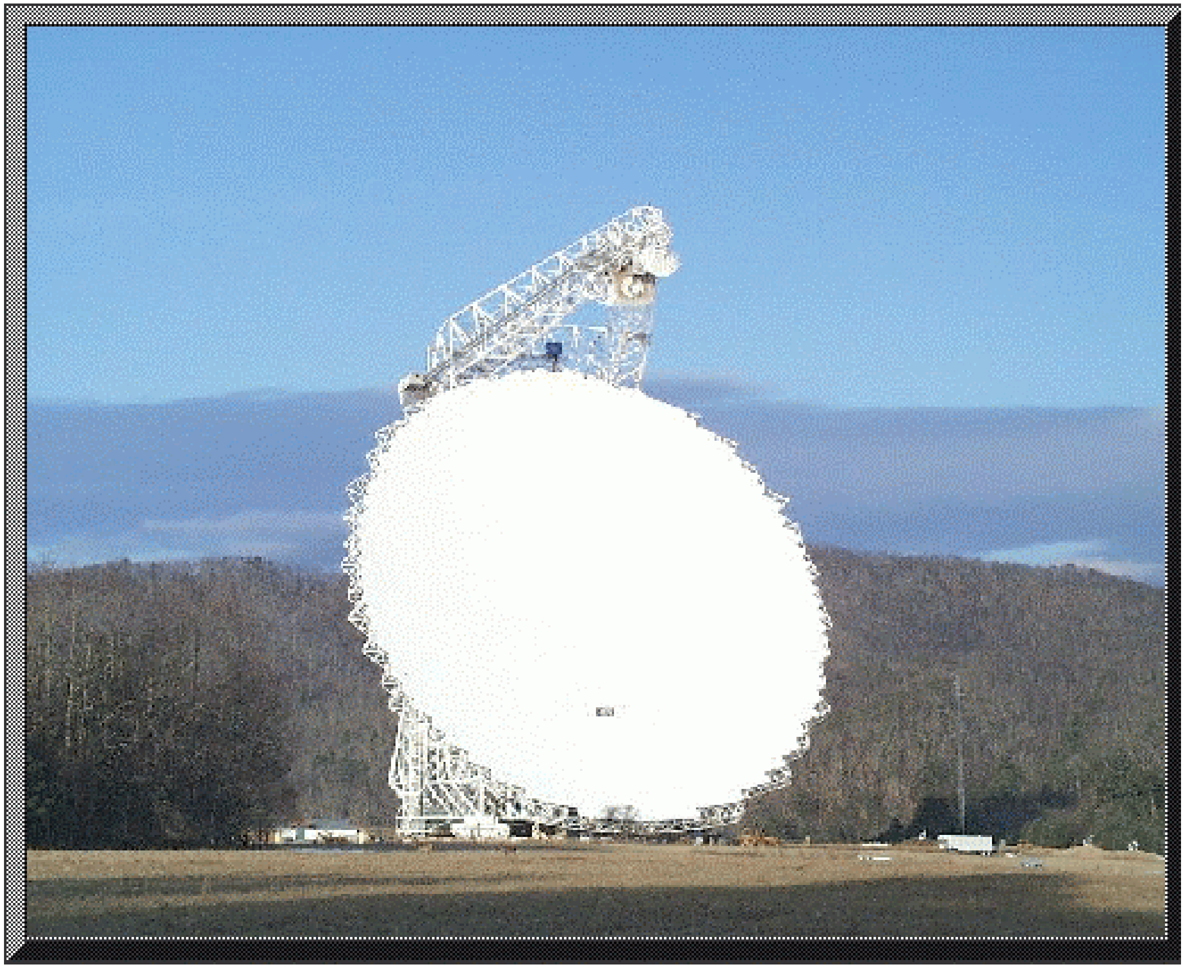
- Come in two basic flavors:

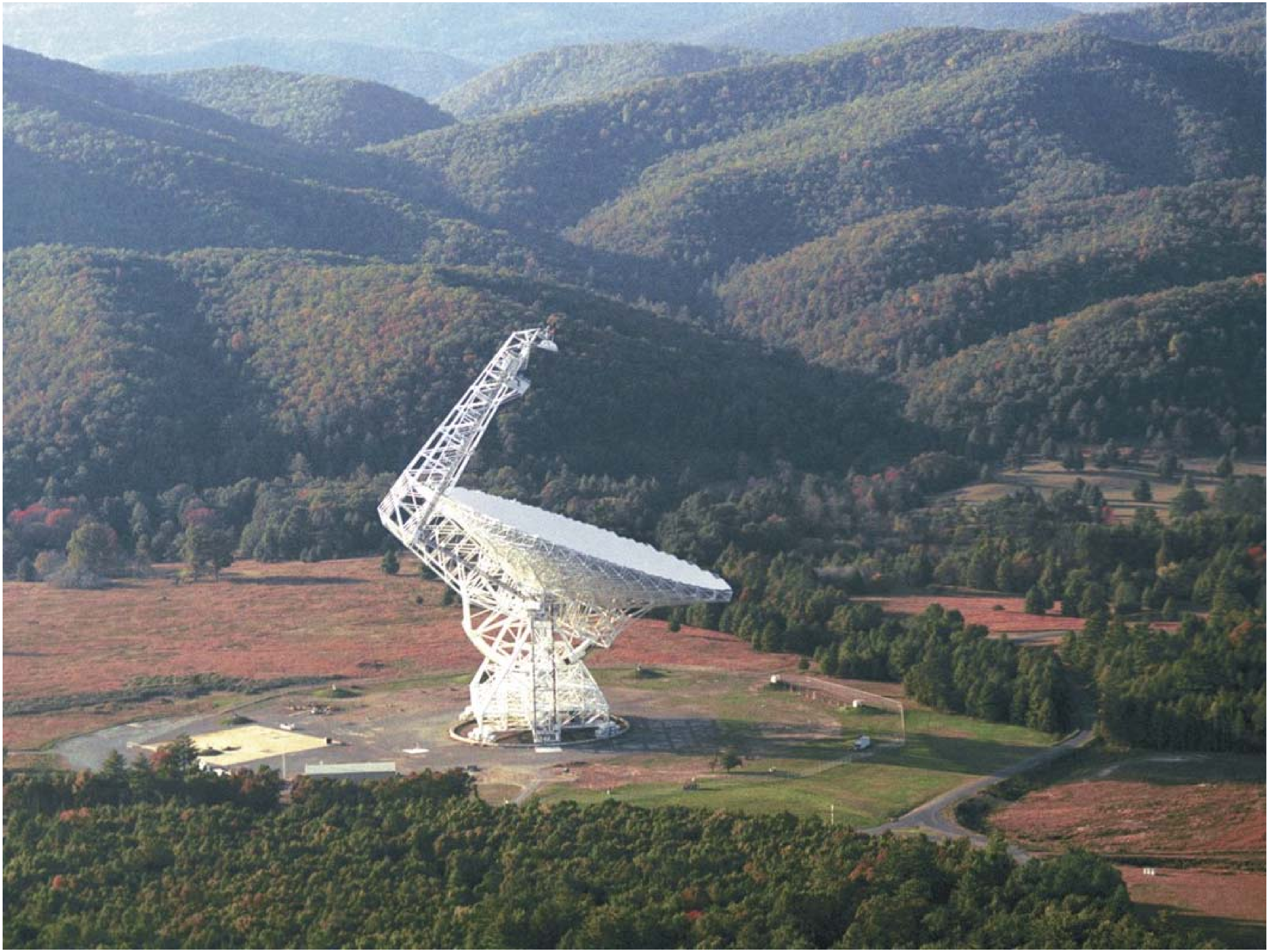
Single Dish

Arrays

Robert C. Byrd Green Bank Telescope

- 2000 dedication
- Operated from West Virginia
- 100 x 110m, novel offset design
- Just coming into full operation



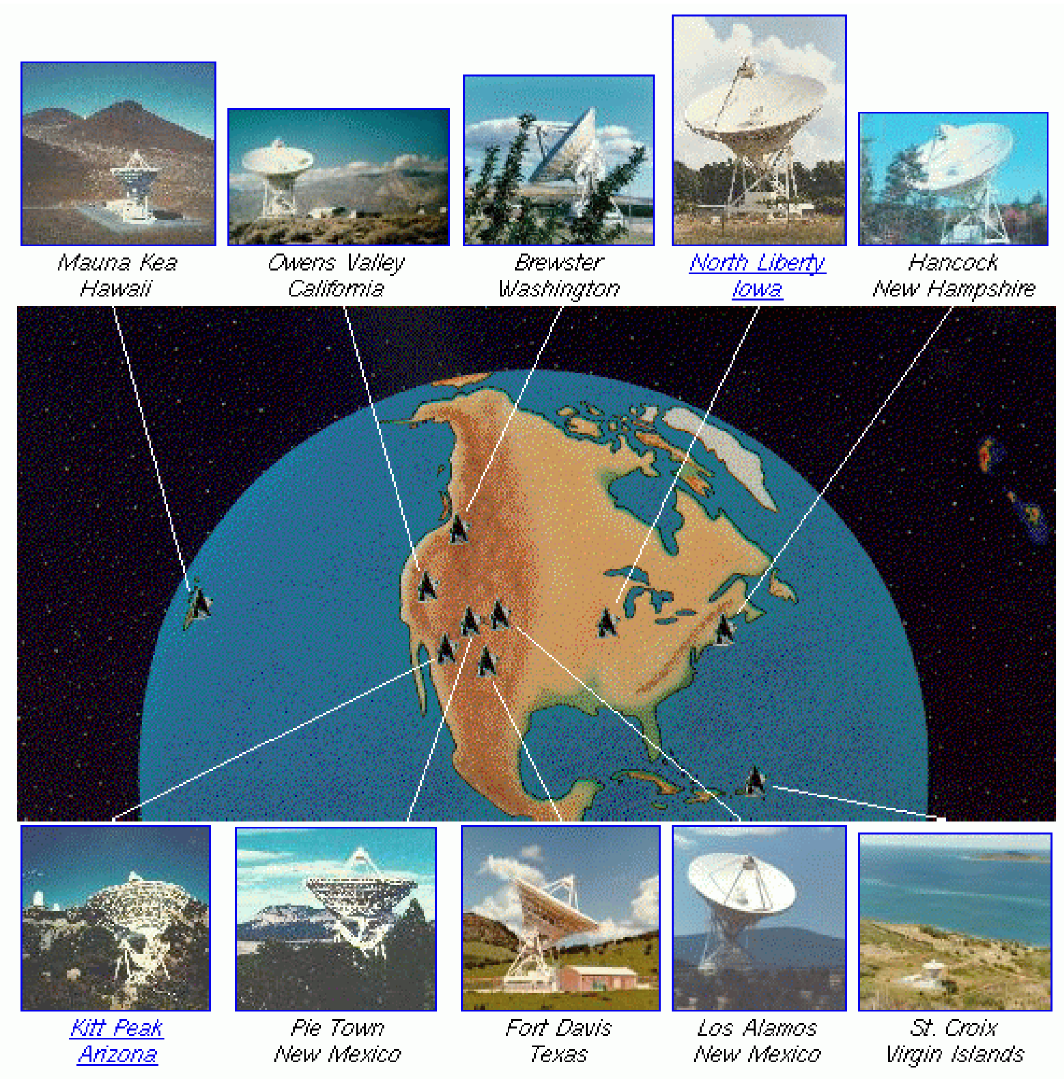


The Very Large Array (VLA)

- 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

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

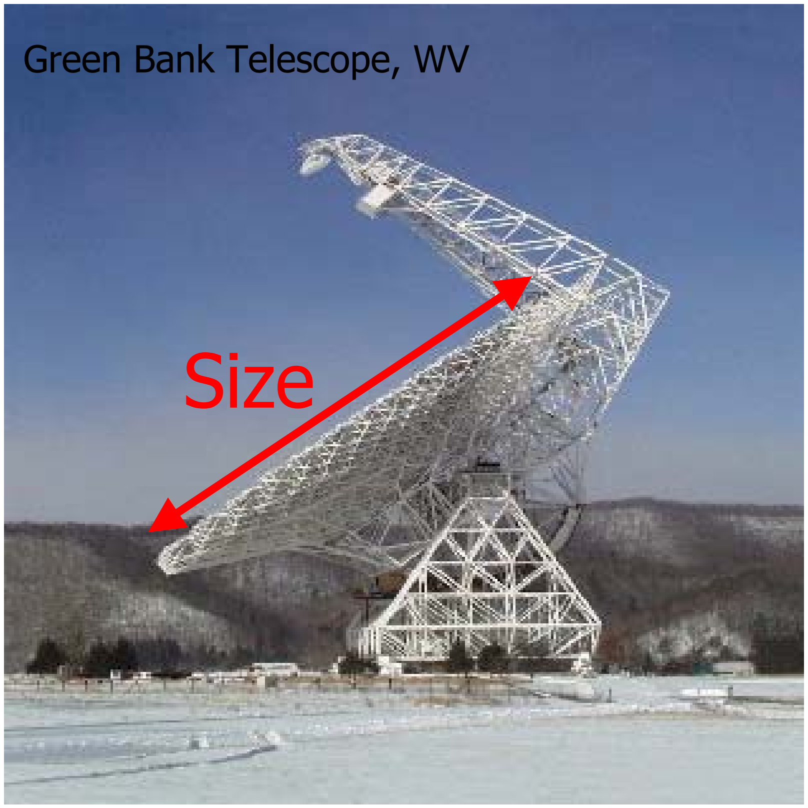
$$\frac{\lambda}{\text{size}}$$

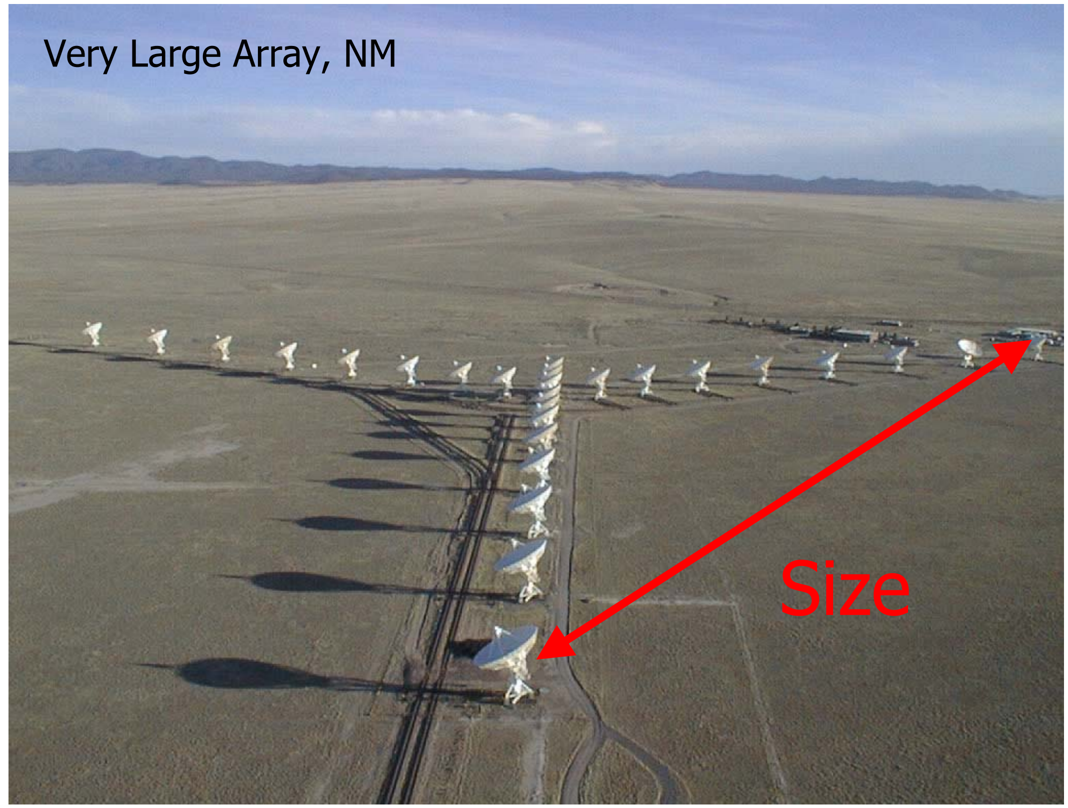
For radio waves, this is large…

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

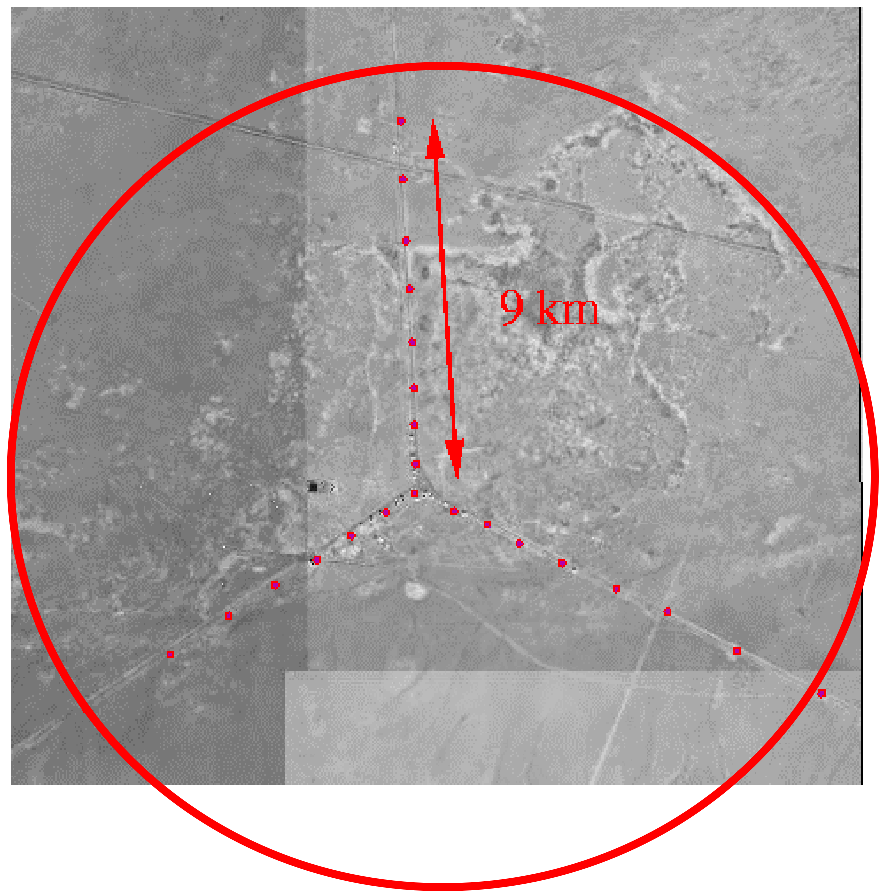
Reconfigurable Arrays: Zoom Lens Effect

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

VLBA

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

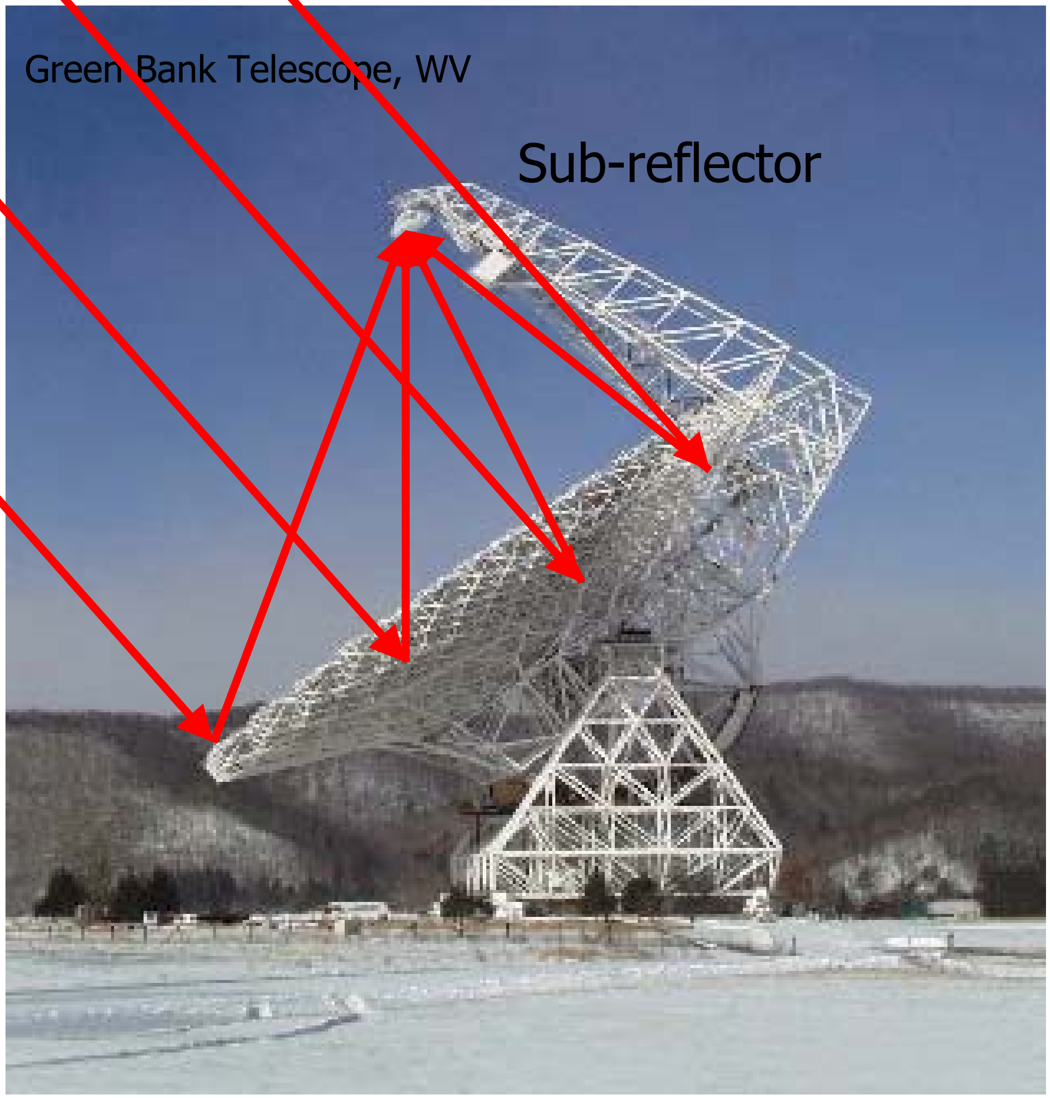
Basic Elements of a Radio Antenna

VLBA Antenna:

- 25 meters (82 feet) in diameter
- As tall as a 10-story building
- Weighs 240 tons

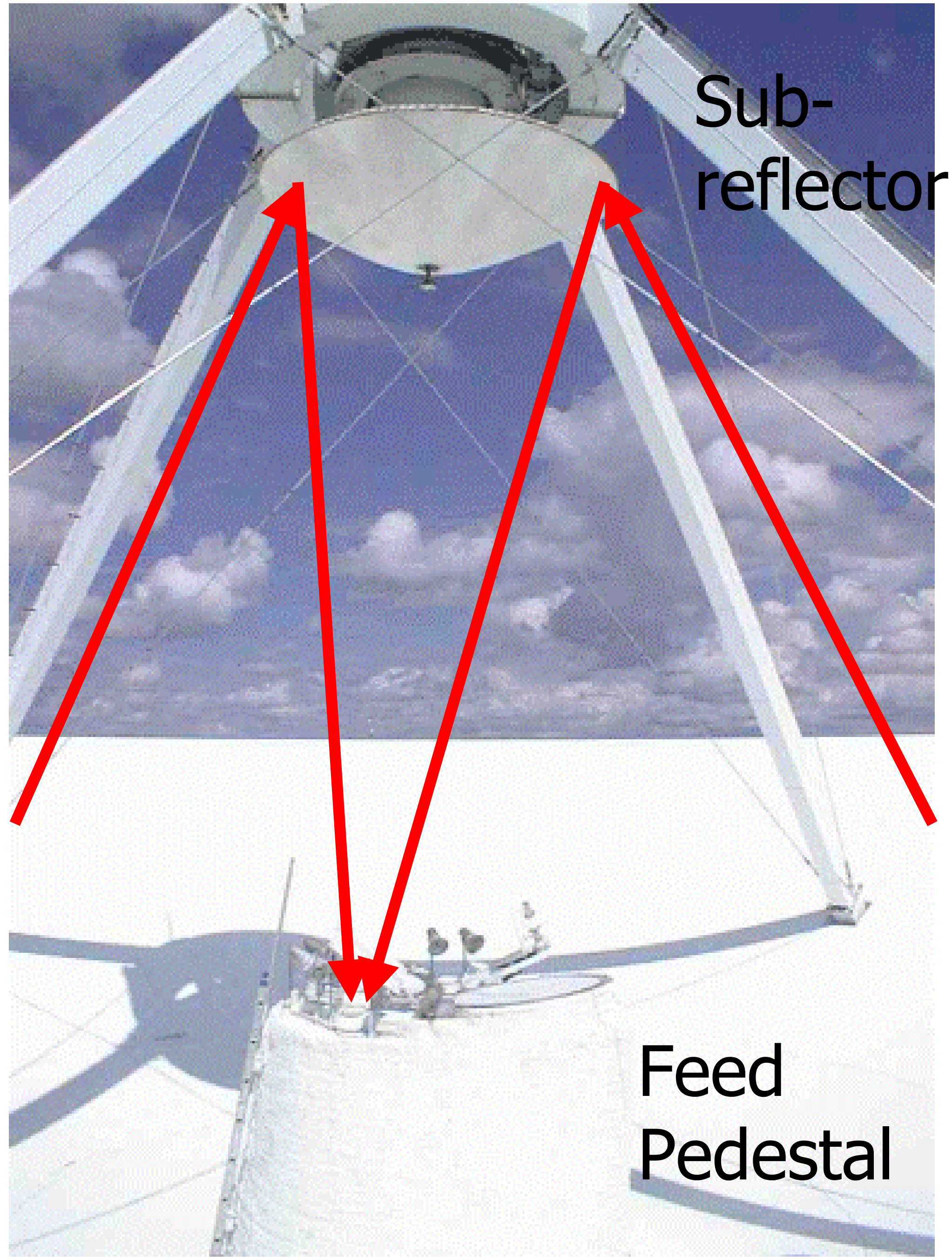
Parabolic Dish

- Aluminum reflecting surface
- Focuses incoming waves to prime focus or sub-reflector



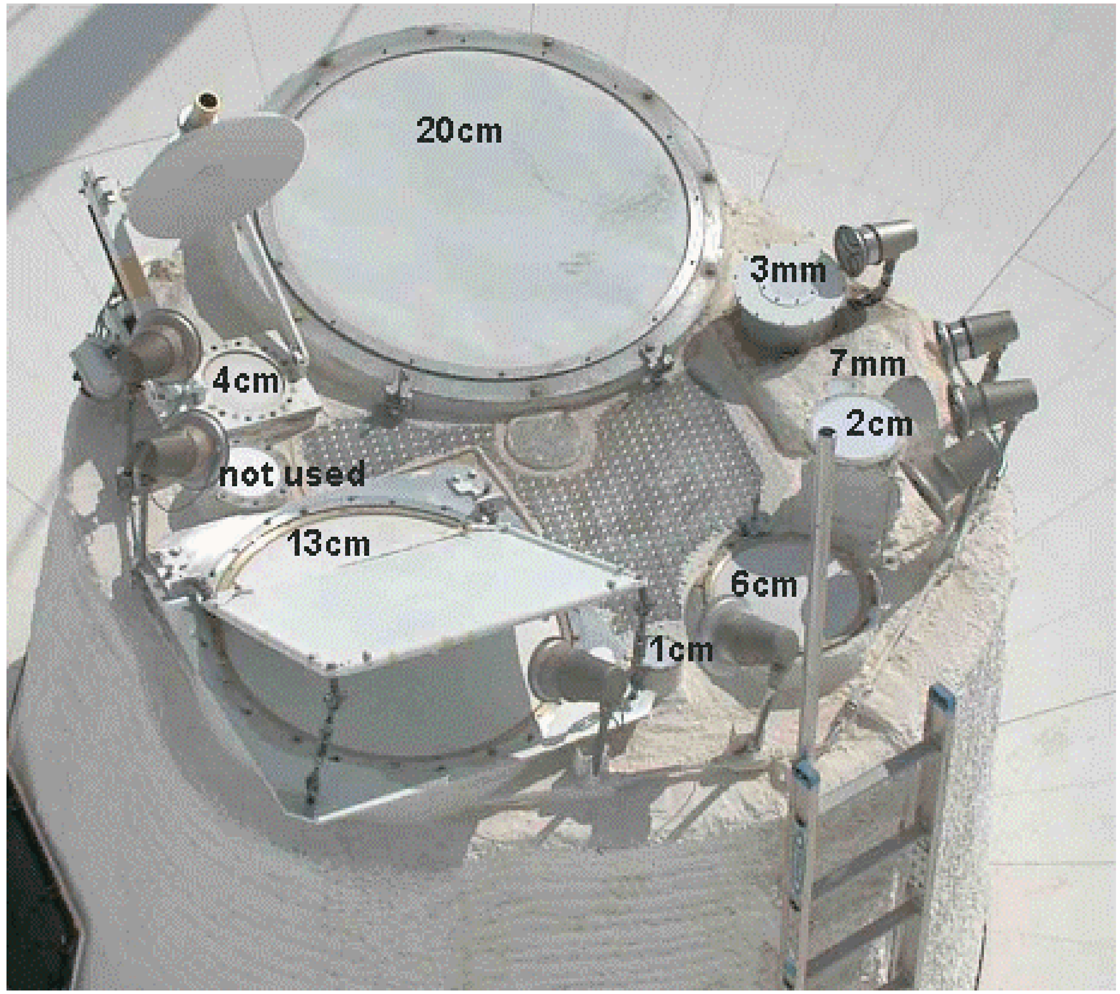
Sub-reflector

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



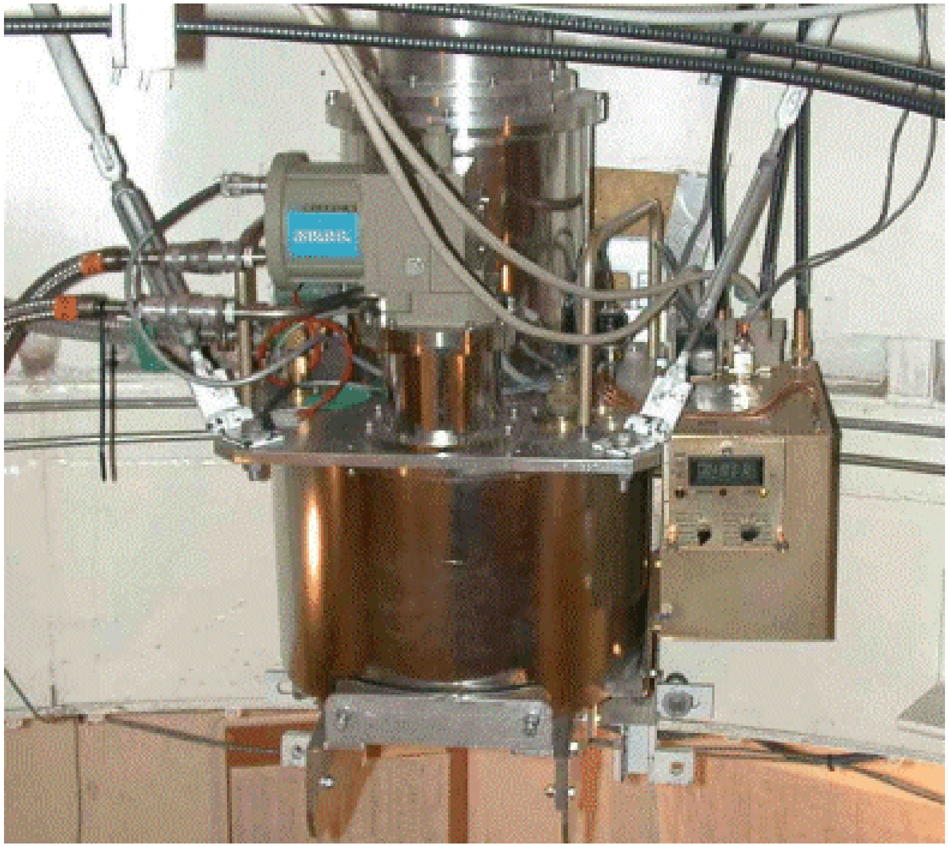
Feed Pedestal

1.5GHz	20cm
2.3GHz	13cm
4.8GHz	6cm
8.4GHz	4cm
14GHz	2cm
23GHz	1.3cm
43GHz	7mm
86GHz	3mm



327MHz	90cm
610MHz	50cm

Antenna Feed and Receivers



Benefits of Observing in the Radio

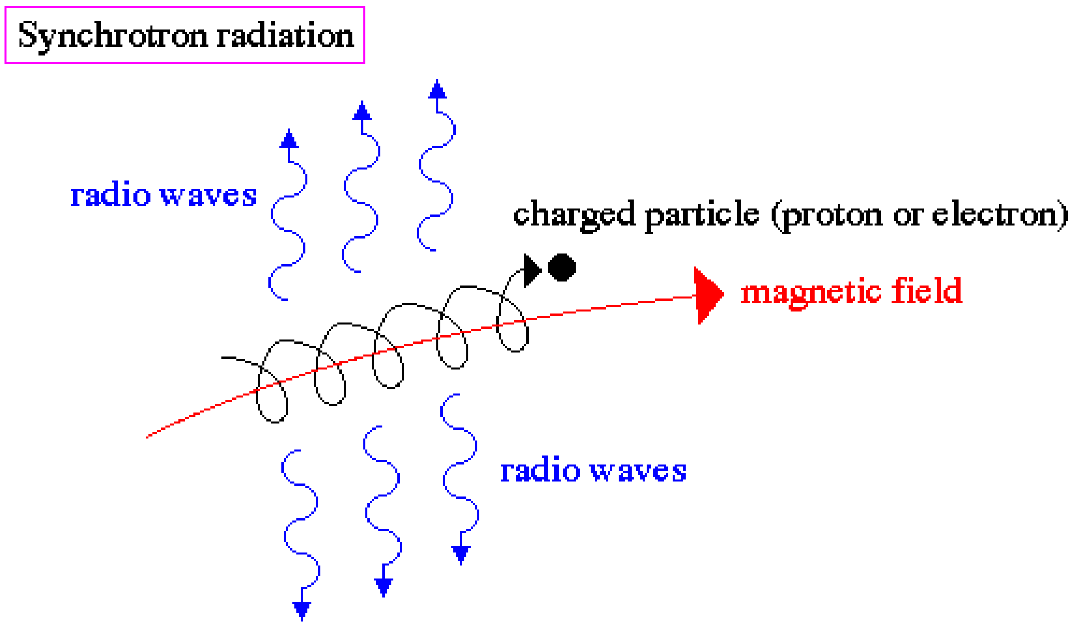
- Track physical processes with no signature at other wavelengths
- Radio waves can travel through dusty regions
- Can provide information on magnetic field strength and orientation
- Can provide information on line-of-sight velocities
- Daytime observing (for cm-scale wavelengths anyway)

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



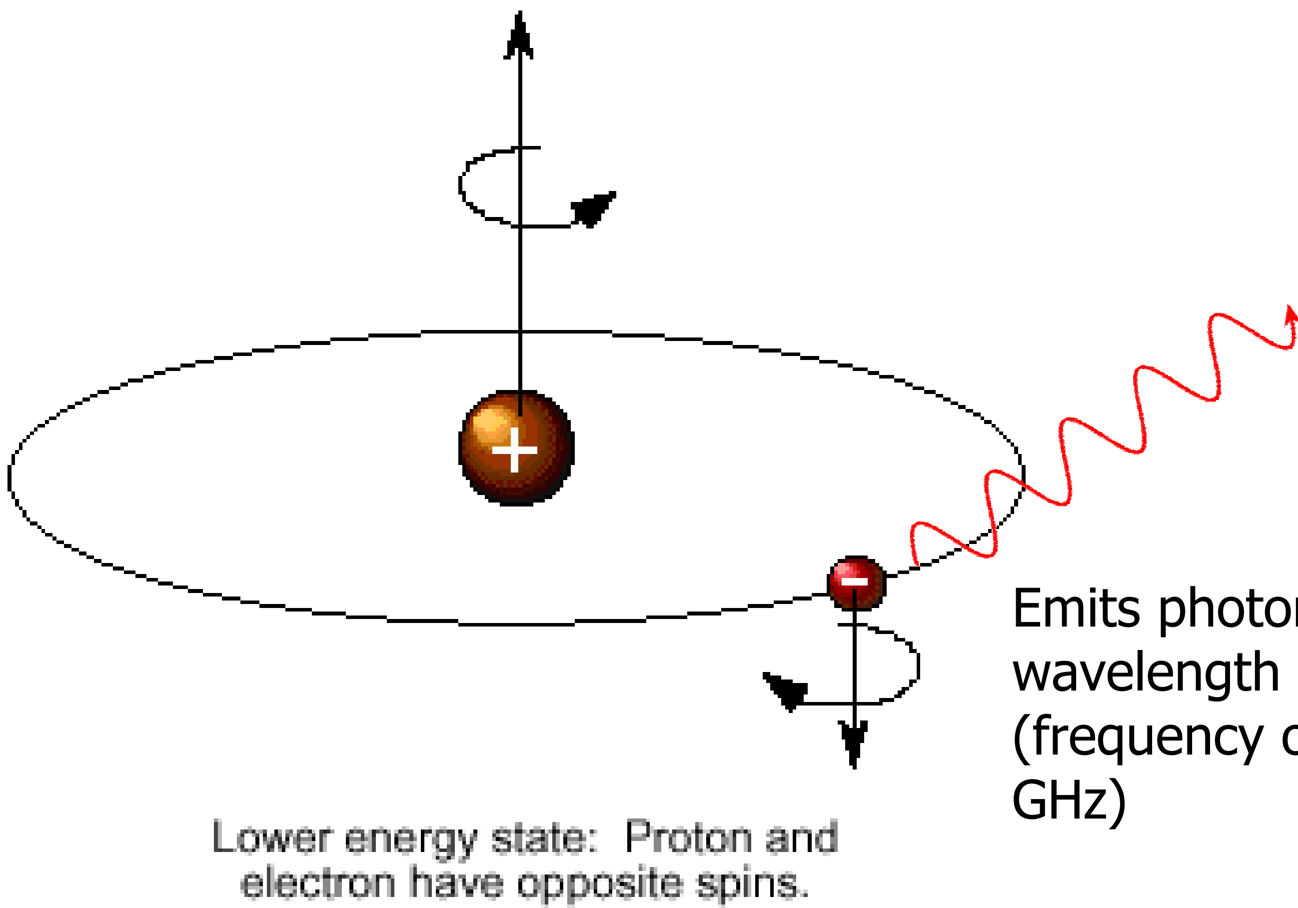
synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

- 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

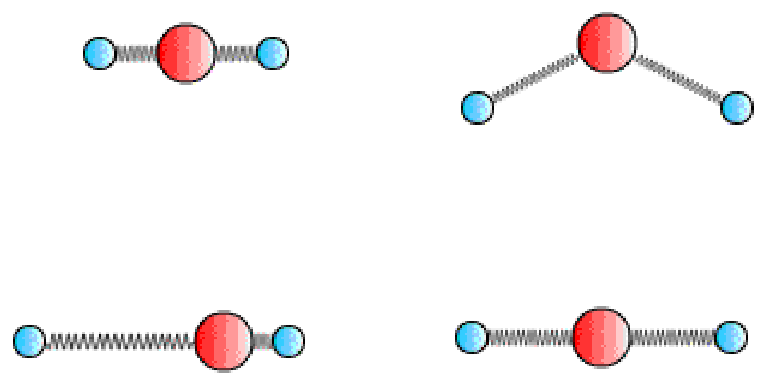


Emits photon with a wavelength of 21 cm (frequency of 1.42 GHz)

Transition probability=3×10^{-15} s^{-1} = once in 11 Myr

Spectral Line emission: molecular rotational and vibrational modes

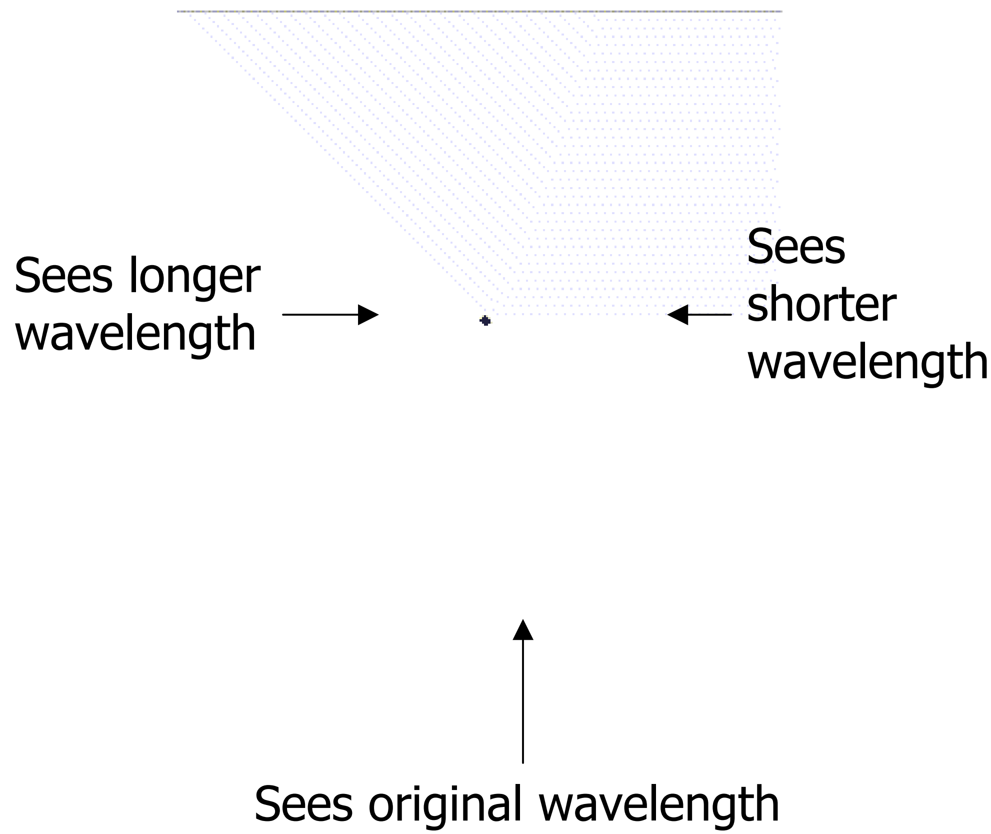
- Commonly observed molecules in space:
  - Carbon Monoxide (CO)
  - Water (H_2O), OH, HCN, HCO^+, CS
  - Ammonia (NH_3), Formaldehyde (H_2CO)
- Less common molecules:
  - Sugar, Alcohol, Antifreeze (Ethylene Glycol), …



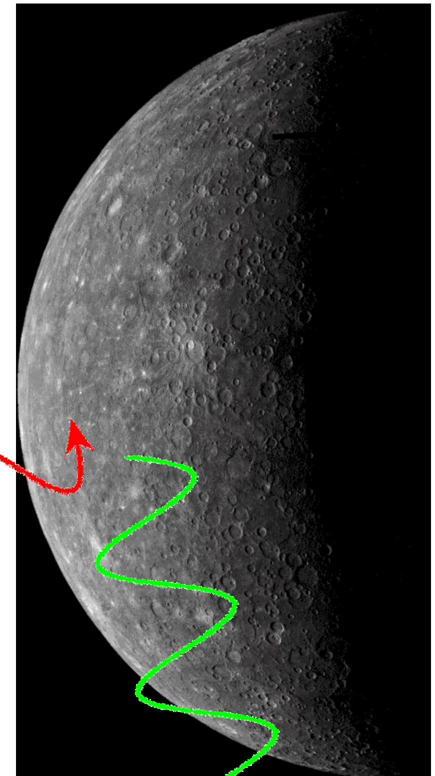
malondialdyde

Spectral Line Doppler effect

- Spectral lines have fixed and very well determined frequencies
- The frequency of a source will changed 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

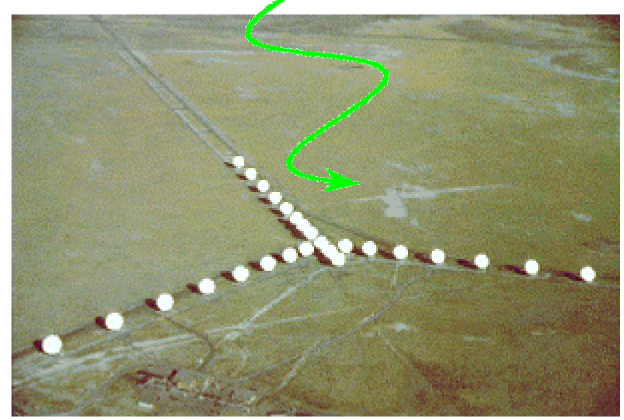


...bounce off object...

Transmit radio wave with well defined frequency...

..observe same frequency

NASA's Goldstone Solar System Radar



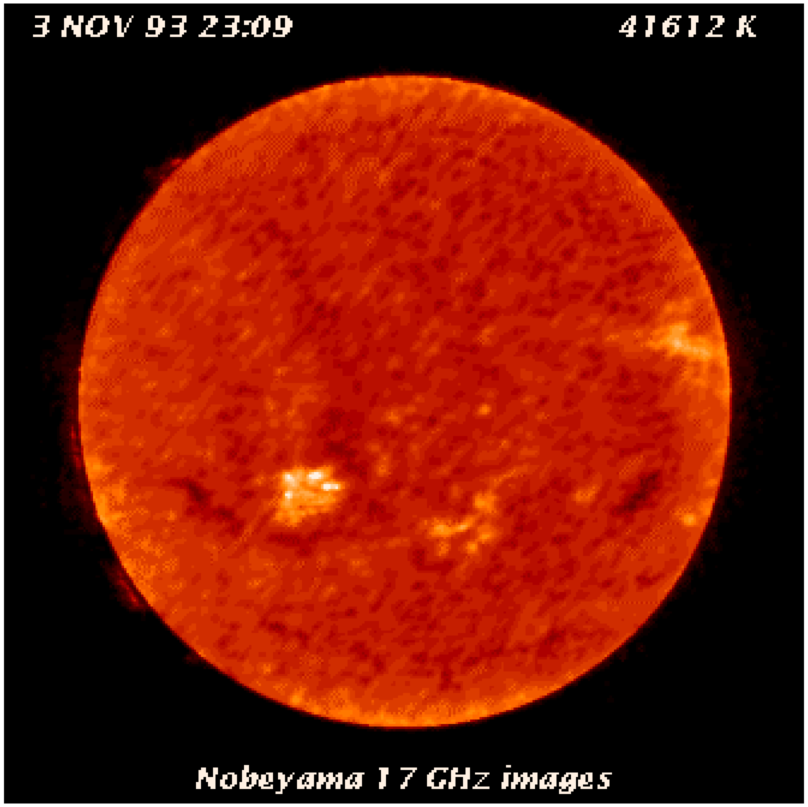
Very Large Array

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

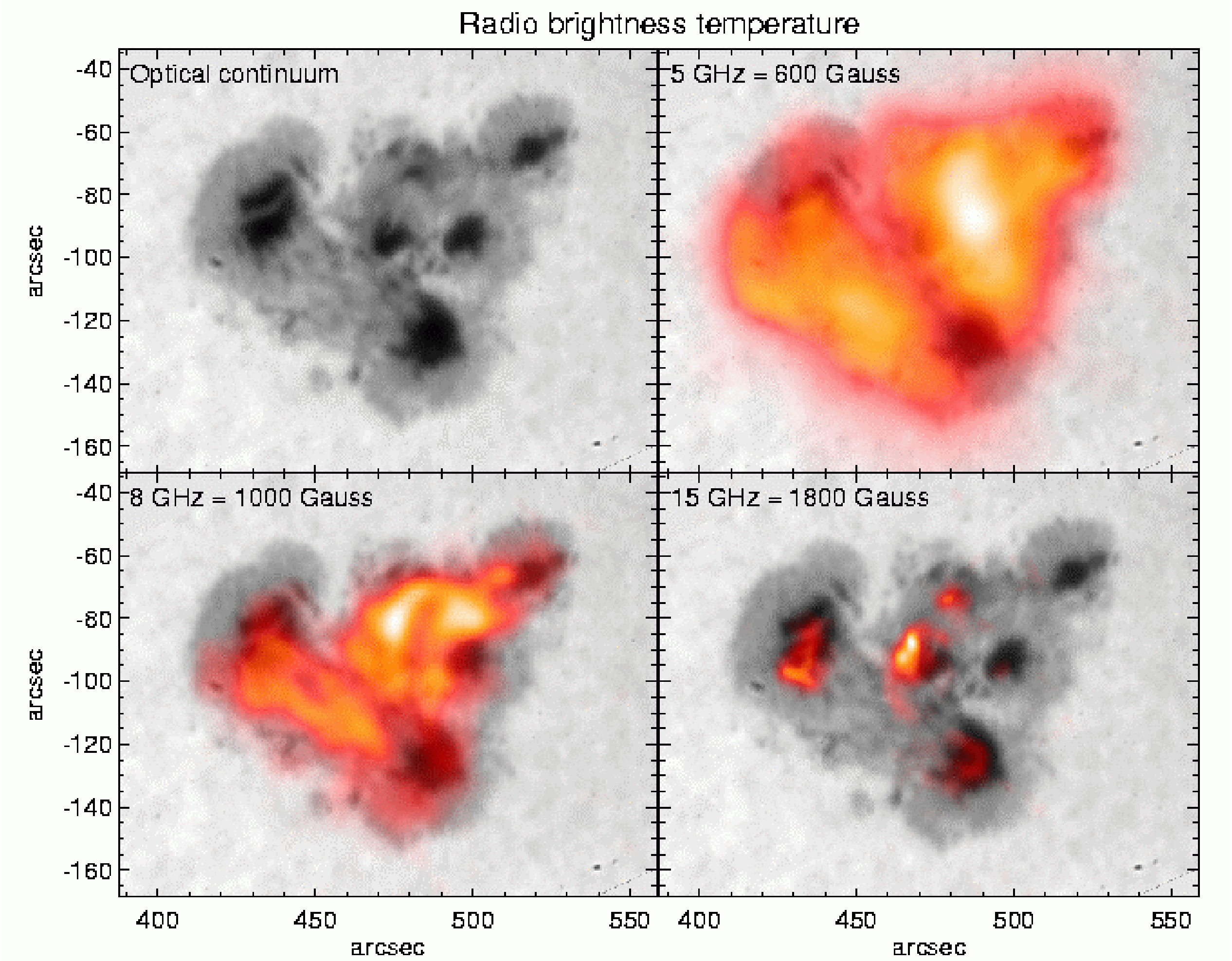
Our Star, The Sun

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



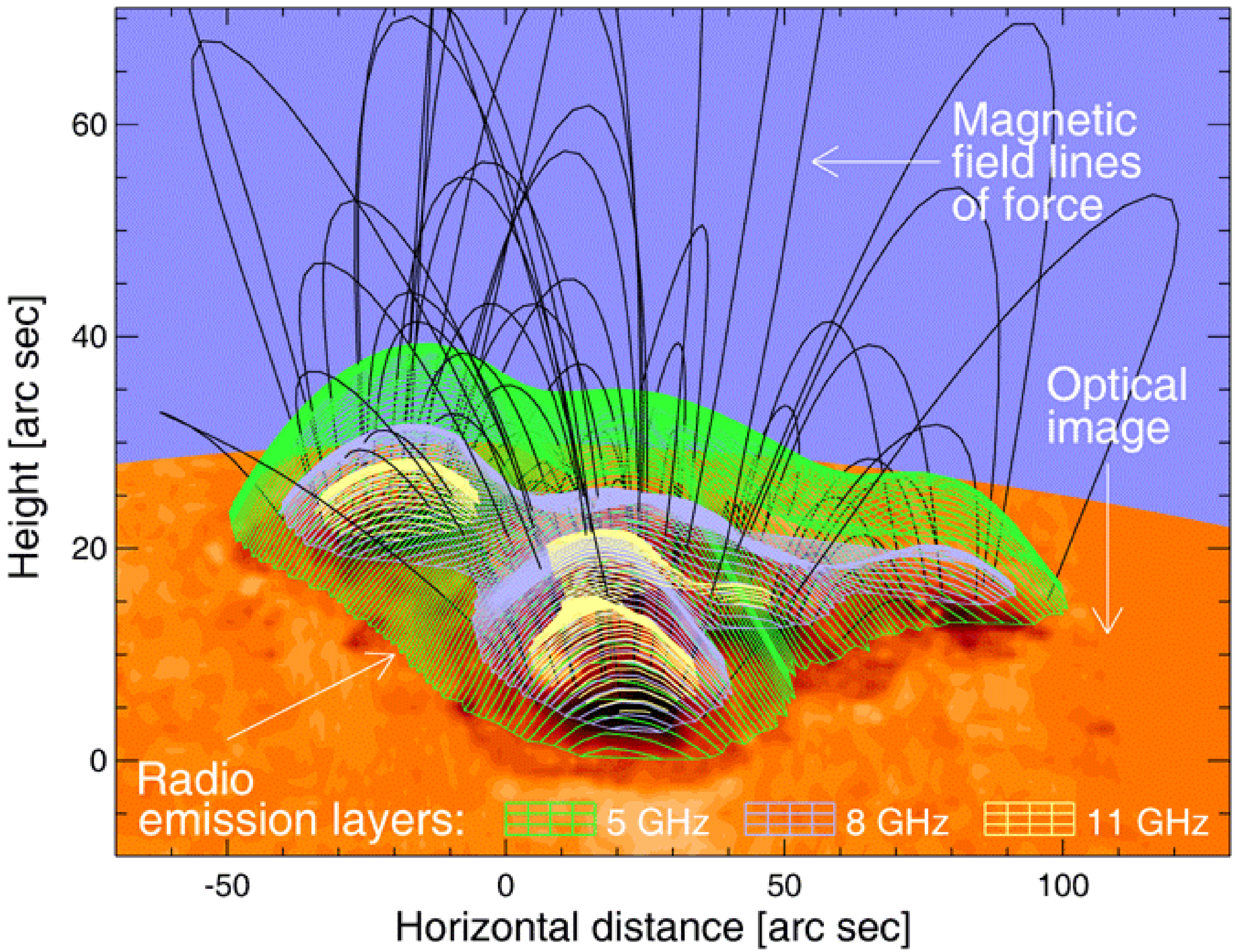
Courtesy Steven White (UMd)
Thermal free-free emission from chromosphere and active regions. Dark filaments=dense cool material suspended in the corona

Solar Magnetic Field Strength and Structure



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

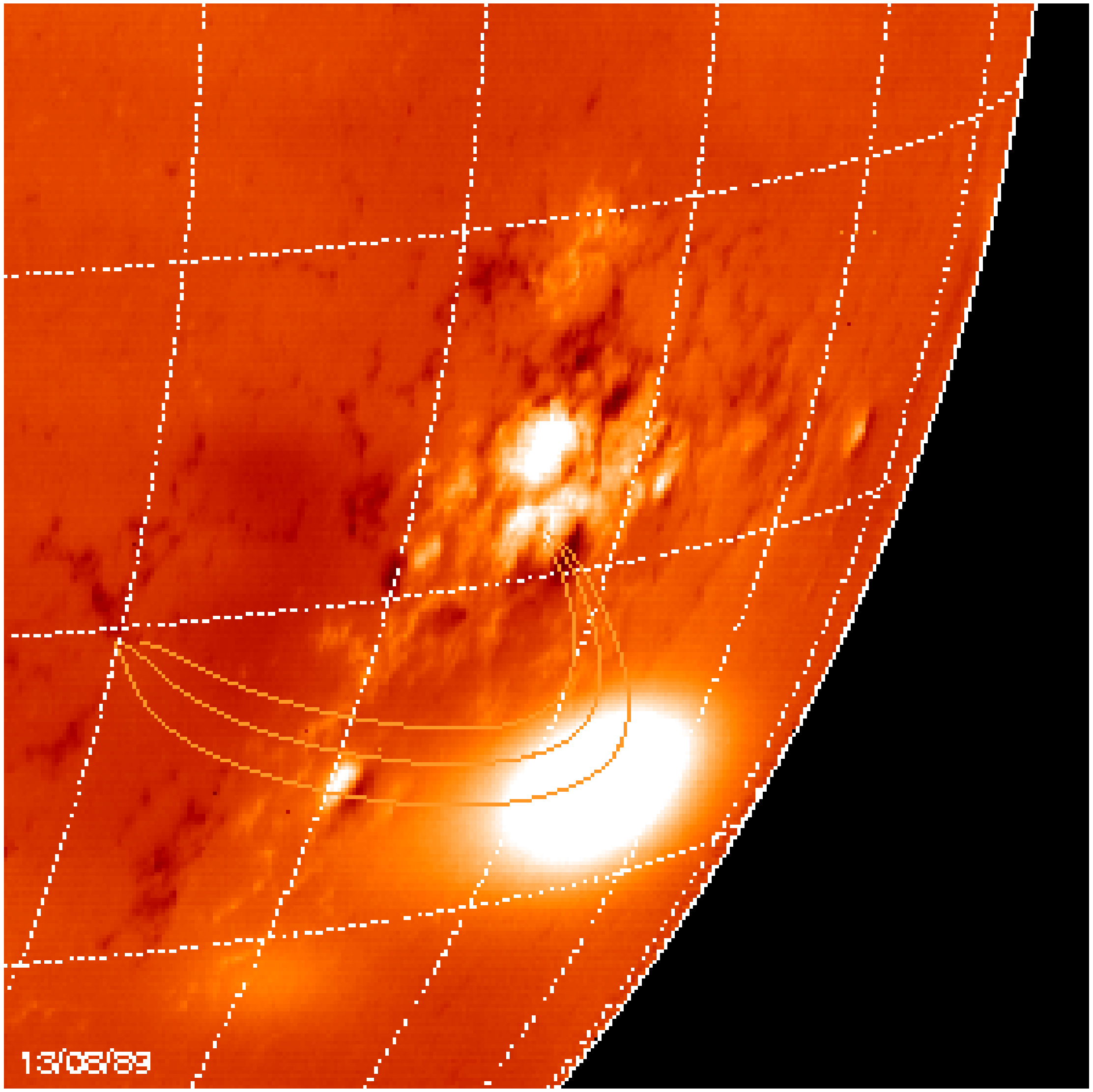
from Lee et al (1998)



Magnetic field lines of force
Optical image
Radio emission layers:
5 GHz
8 GHz
11 GHz
Height [arc sec]
Horizontal distance [arc sec]
60
40
20
0
-50
0
50
100

Solar Flares

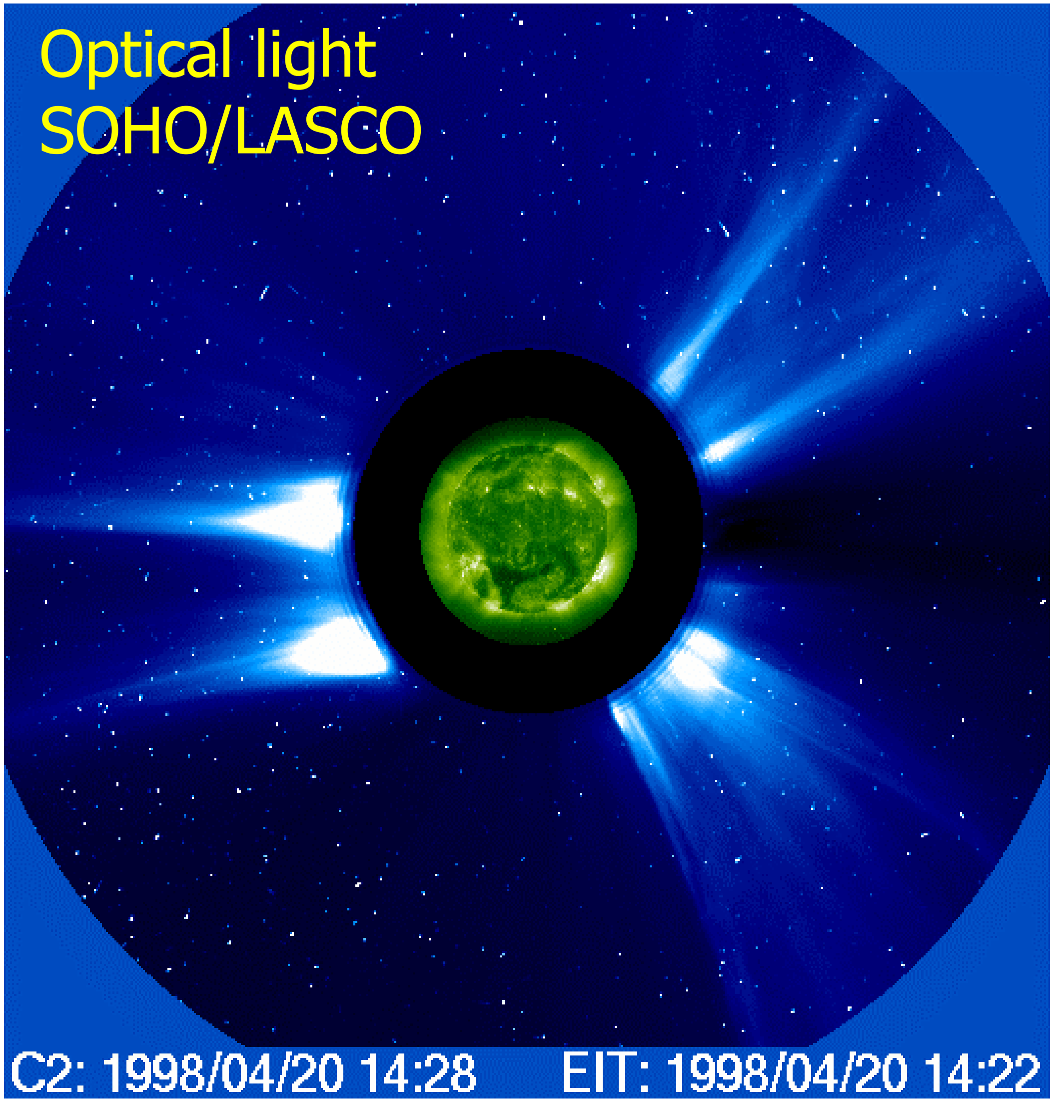
Type U bursts observed by Phoenix/ETH and the VLA.



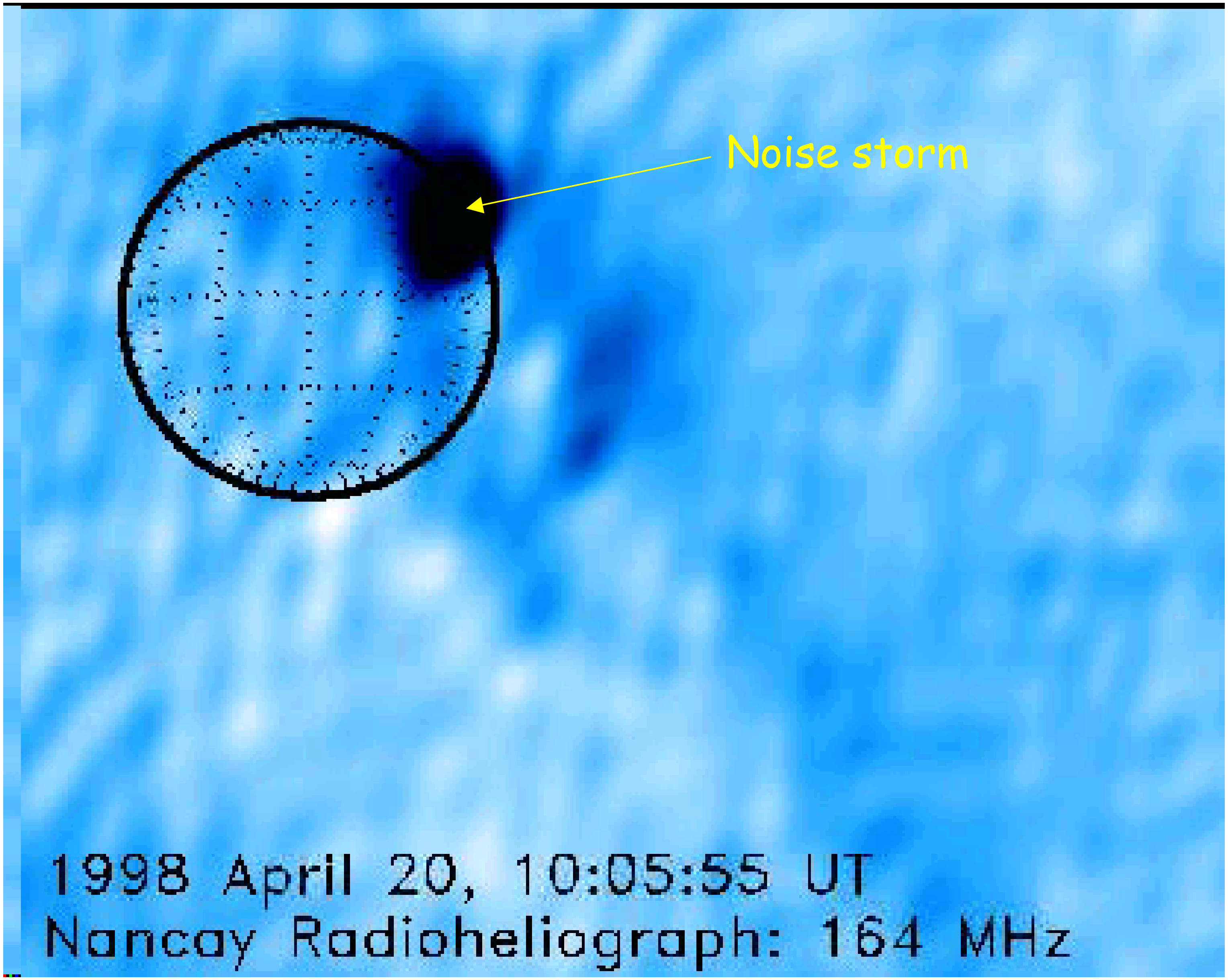
Aschwanden et al. 1992

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 navigaton



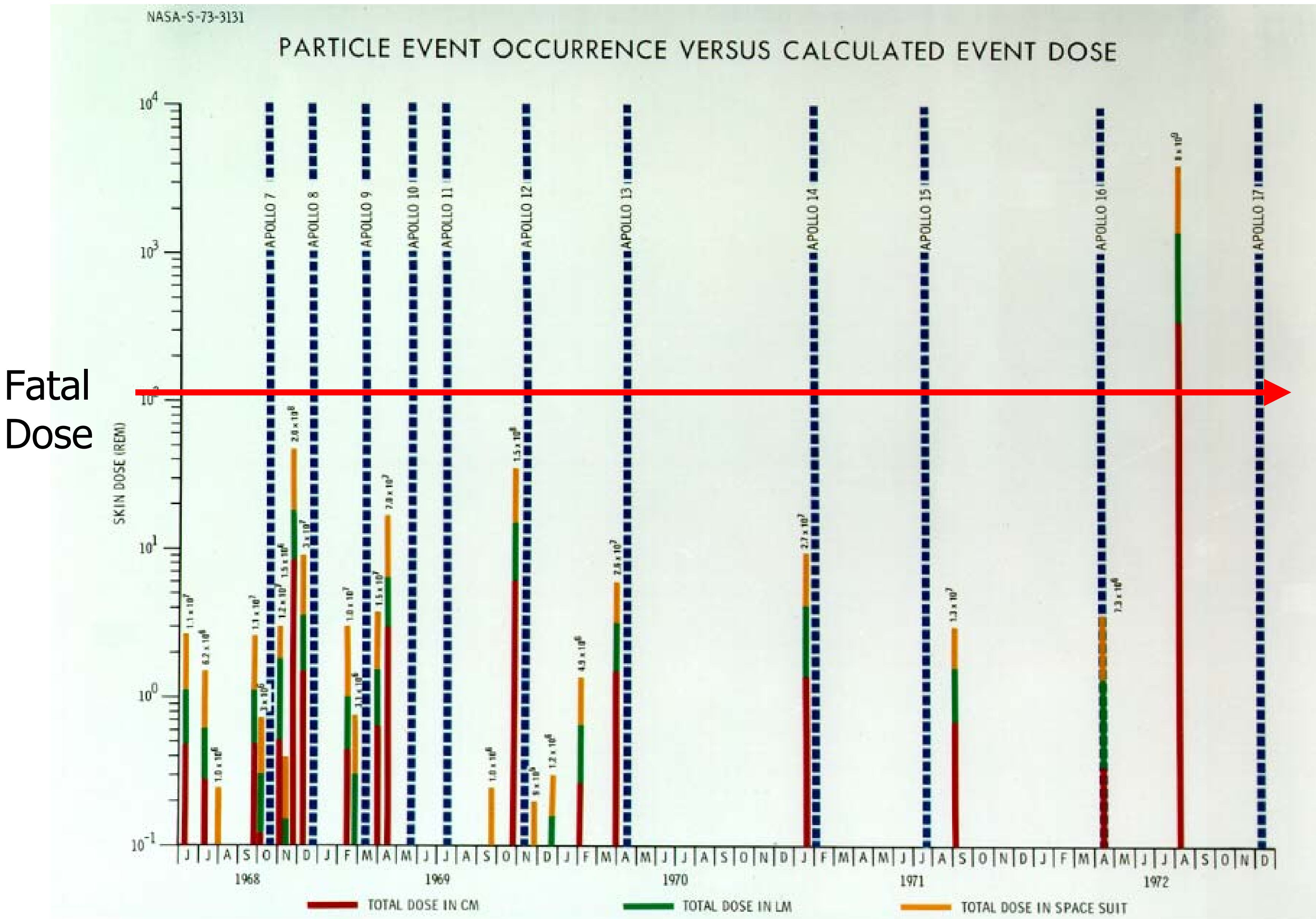
cdaw.gsfc.nasa.gov/CME_list/



Synchrotron Radiation from MeV electrons. B~1 Gauss

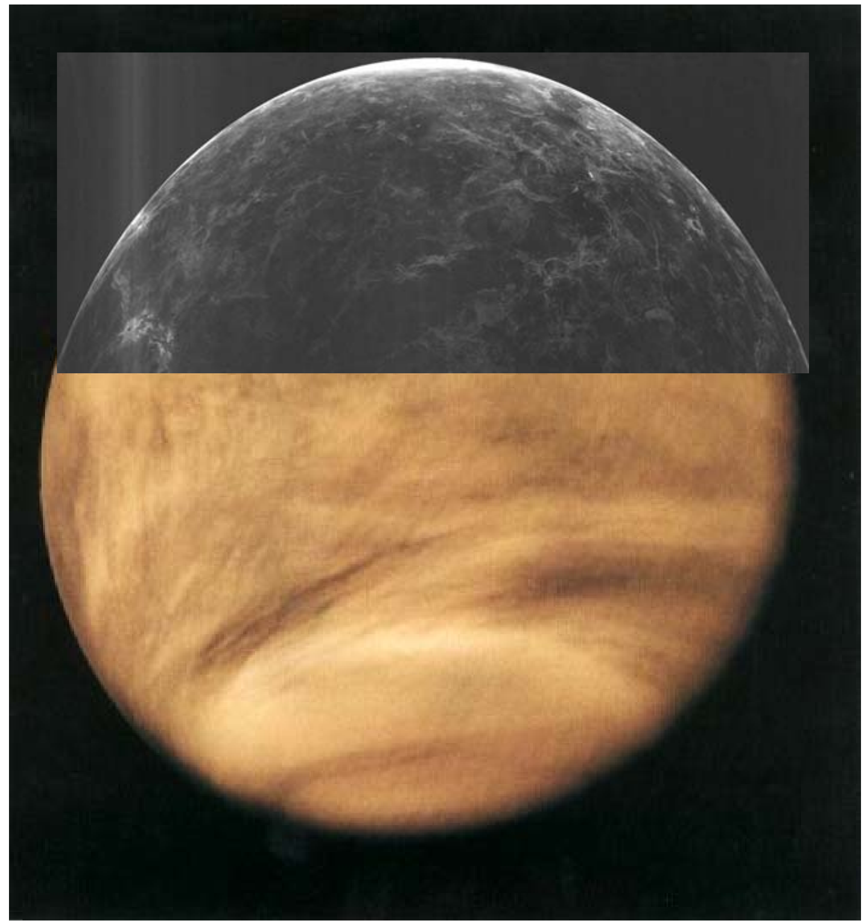
Bastian et al. (2001)

Particles accelerated during Solar Flares and CMEs can seriously impact interplanetary travel



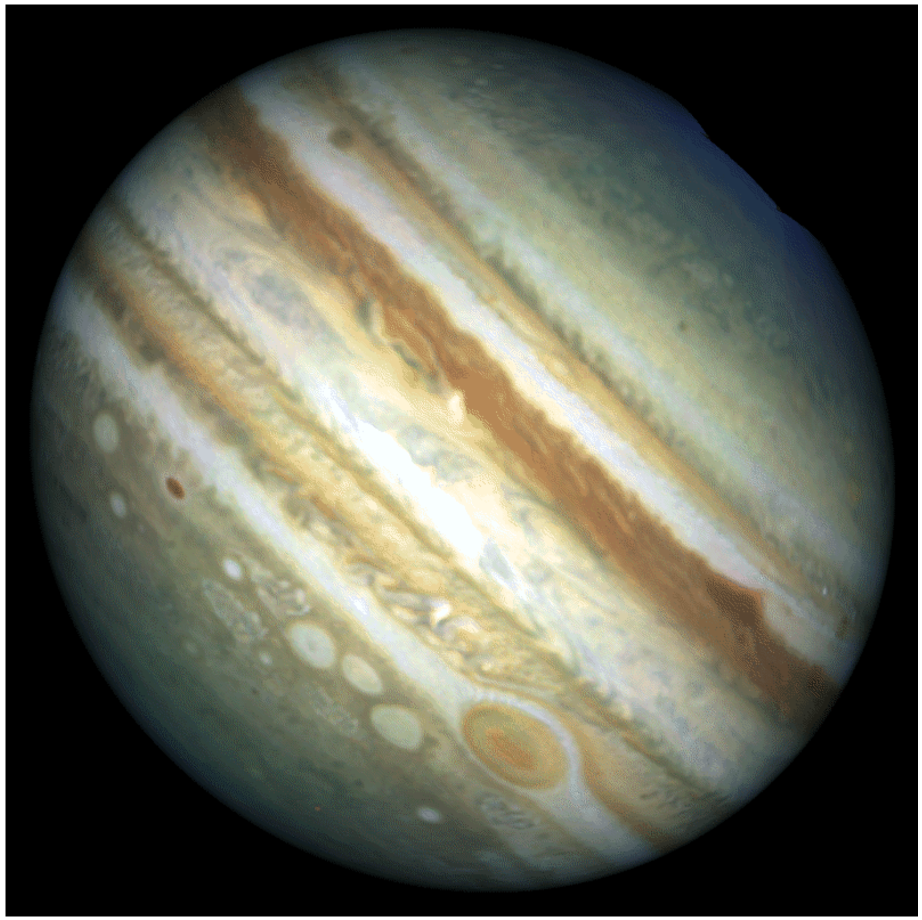
Venus

- 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

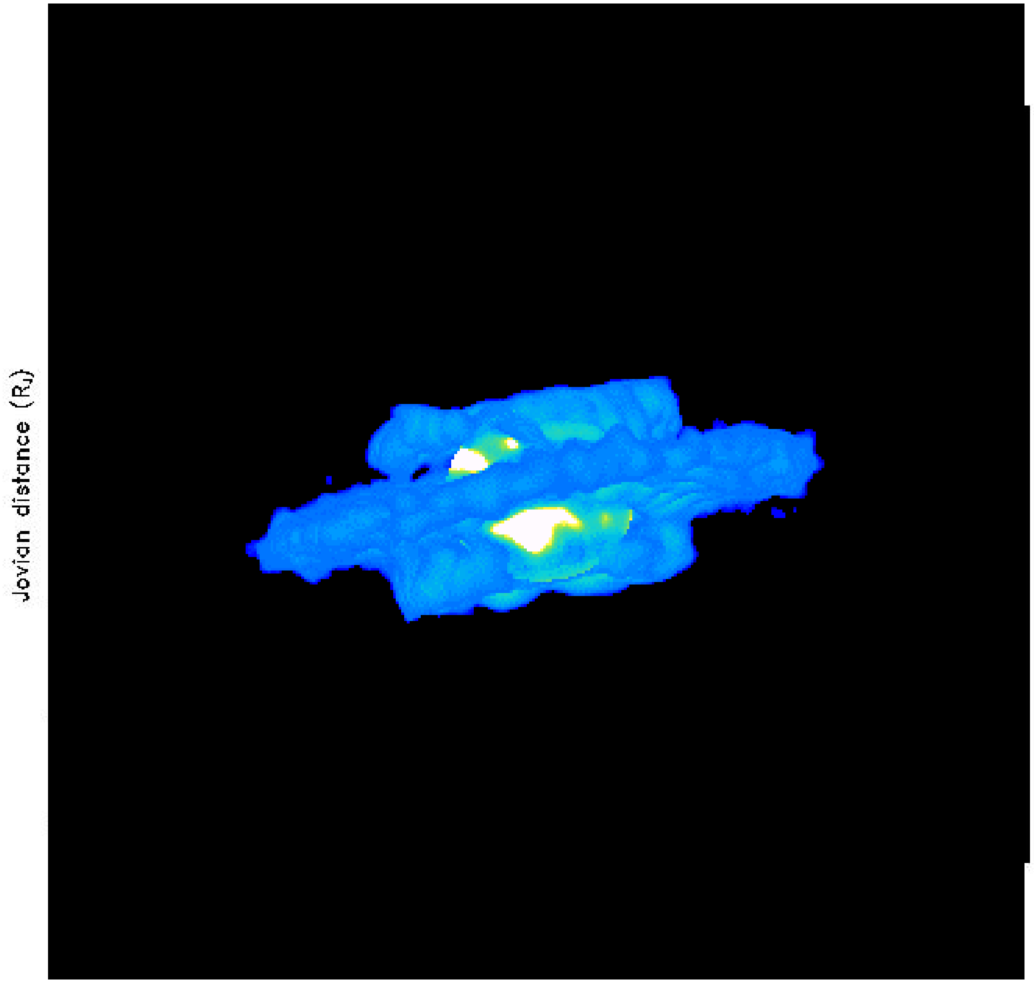
Jupiter



Jupiter - Synchrotron

Charged particles trapped in Jupiters magnetic field
Similar to earths Van Allen belt

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



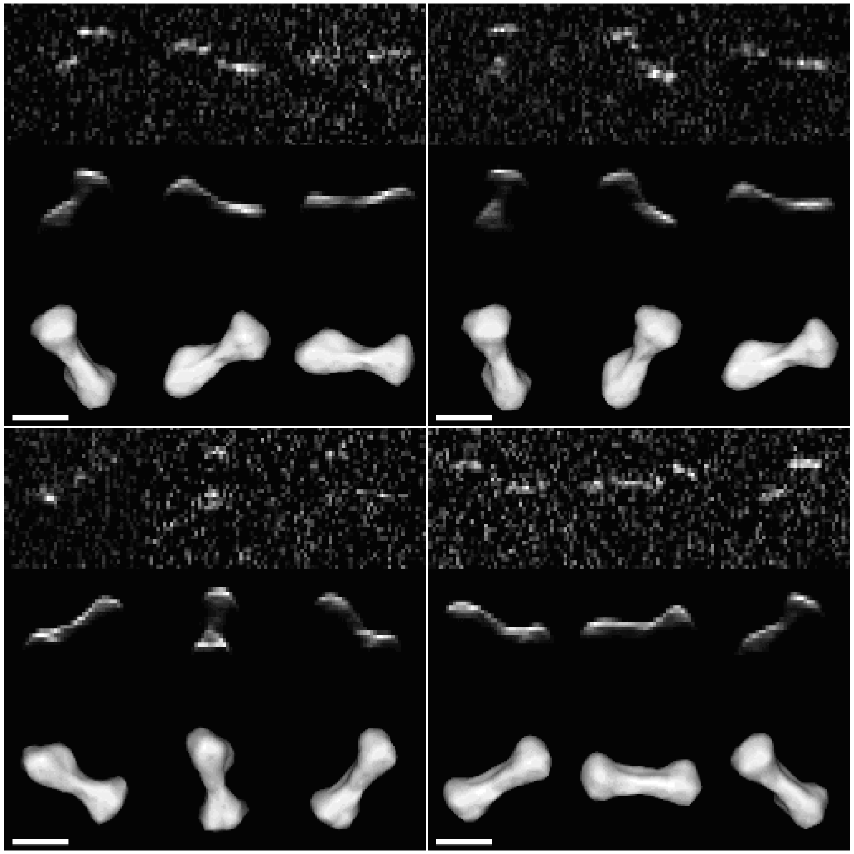
Observations: VLA 20 cm
De Pater, Schulz & Brecht 1997

3-D model: Sault et al. 1997; de Pater & Sault 1998

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



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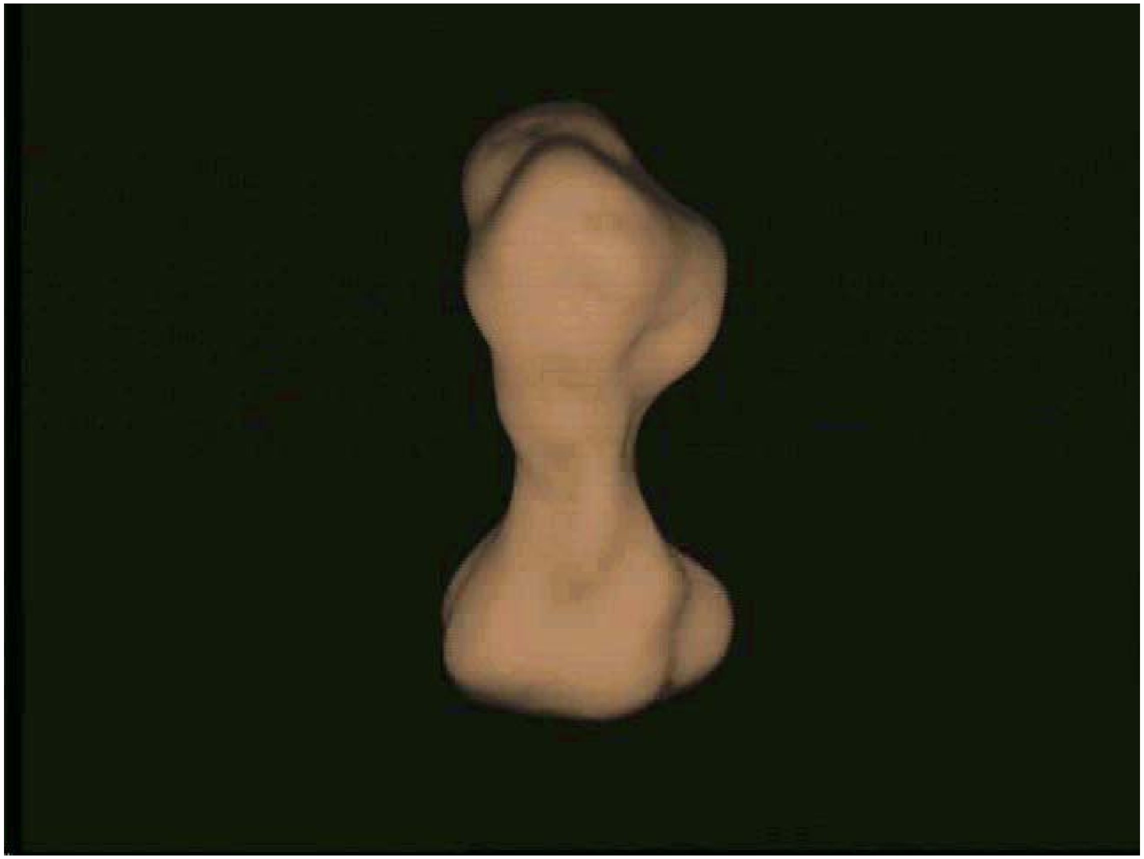


Computer reconstruction by Ostro et al. 2000, Science, 288, 836

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

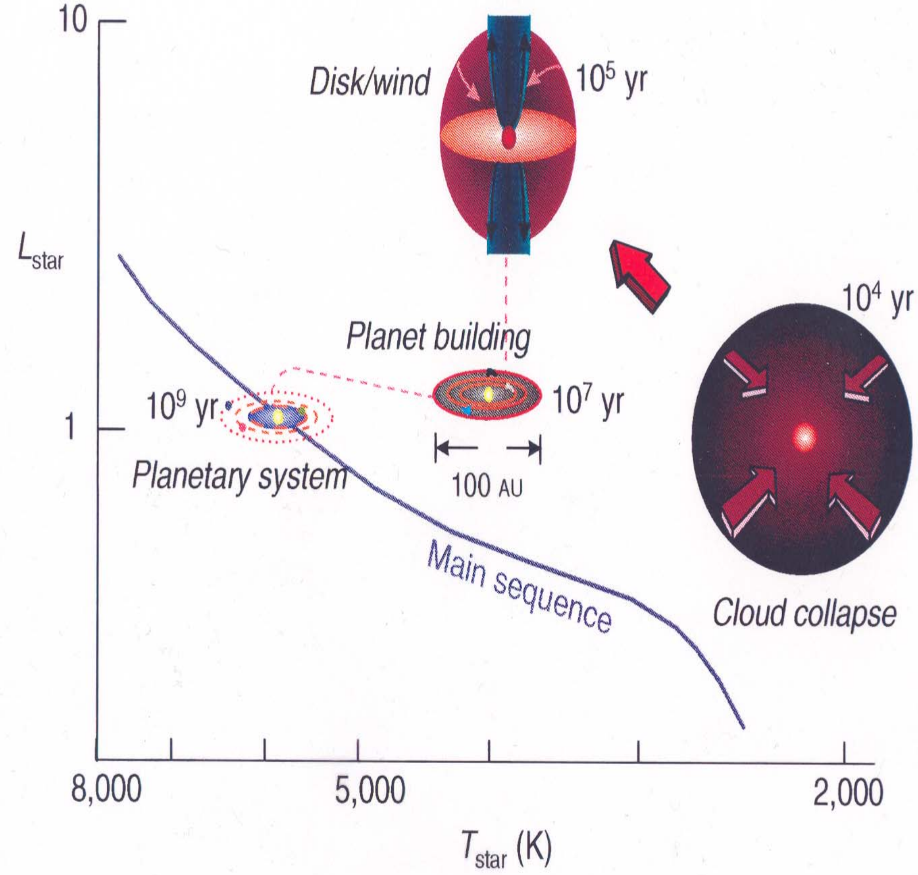
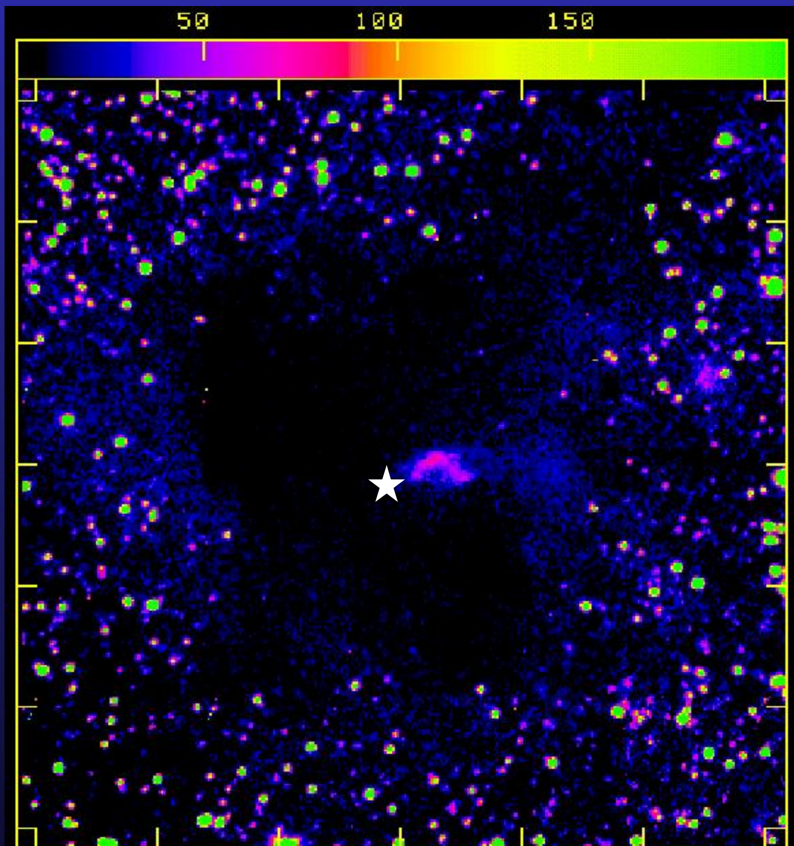


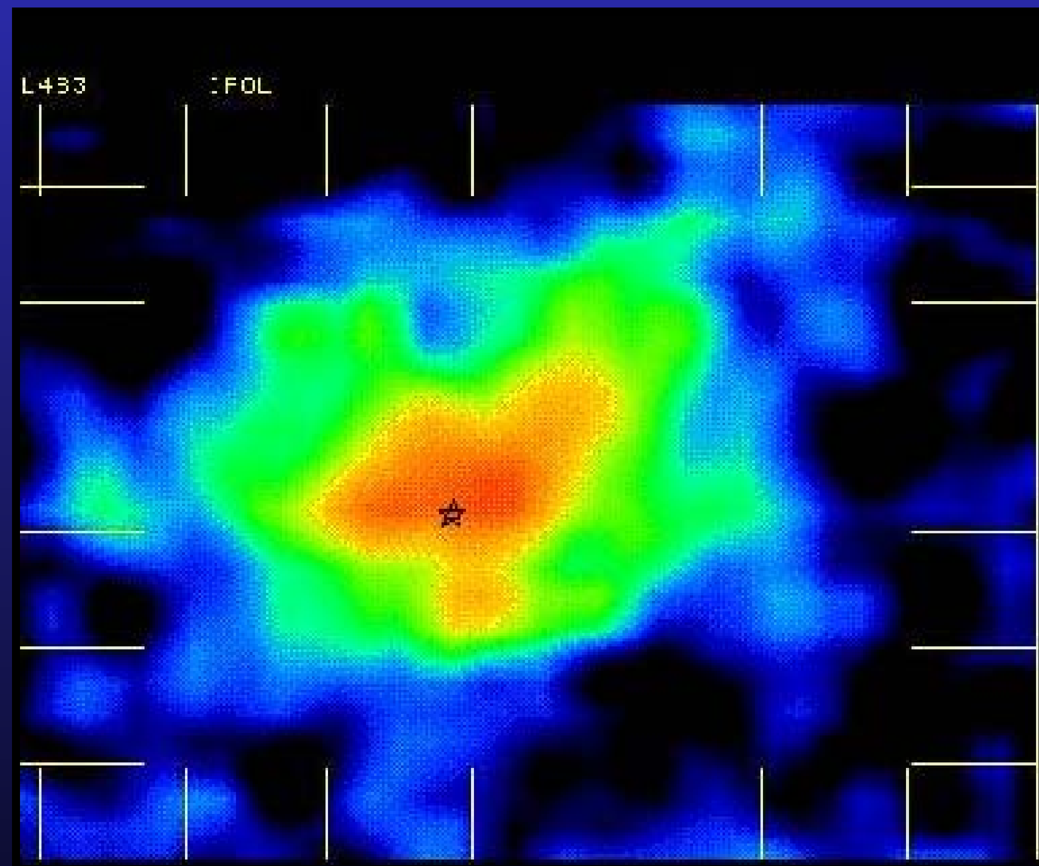
Fig. 2, Beckwith & Sargent, *Nature*, **383**, 139-144.

Dark Star Forming Clouds

L483 Molecular Cloud



Near-infrared (1.2 microns)



NRAO 12-m CO(1-0)

Gas glows most brightly where accretion onto a protostar warms the cloud

A. Wootten & G. Fuller
www.nrao.edu/imagegallery

Proto-stellar Outflows

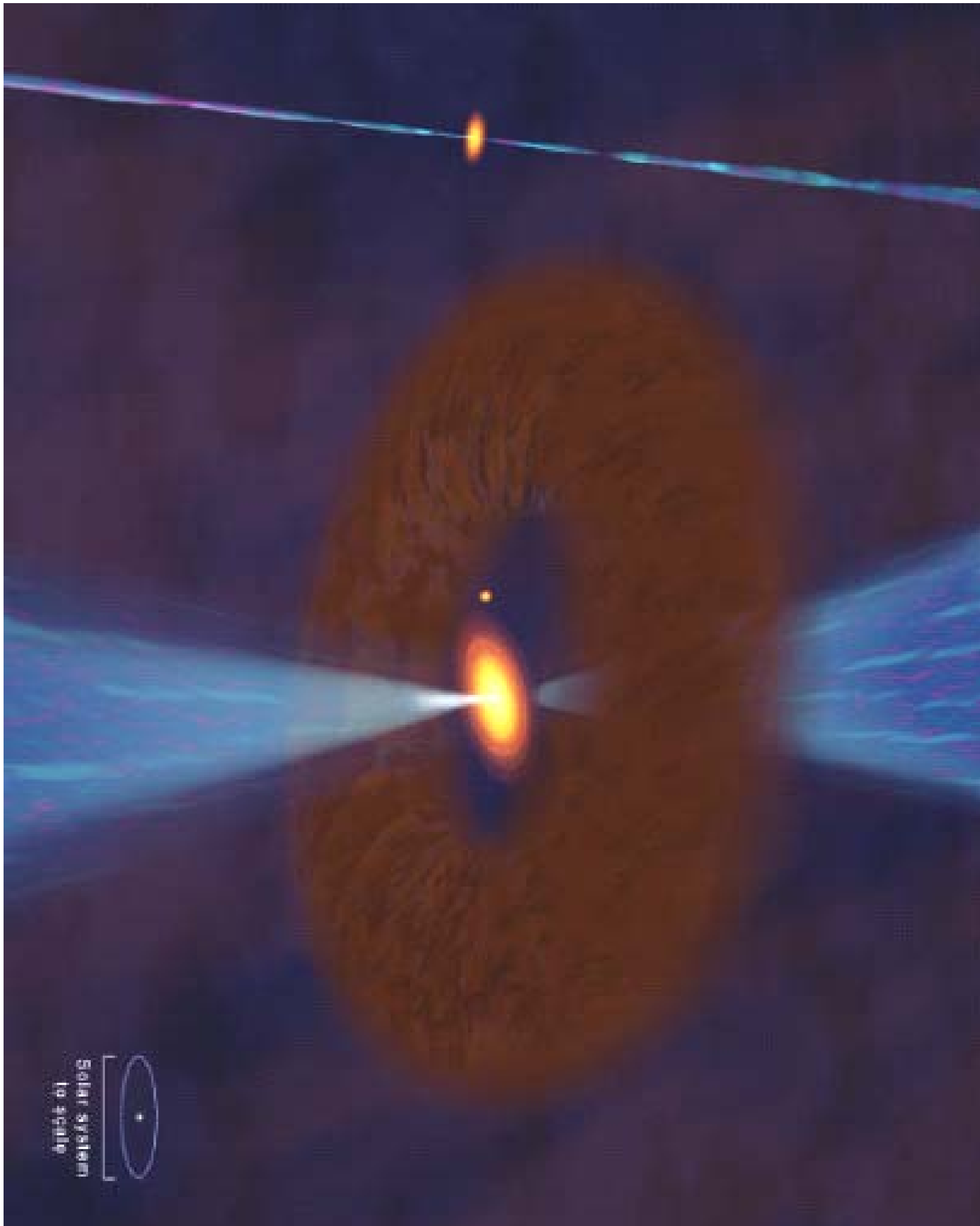
"9 point" radio map of bipolar molecular outflow from the S106 protostar

Blue=Towards us

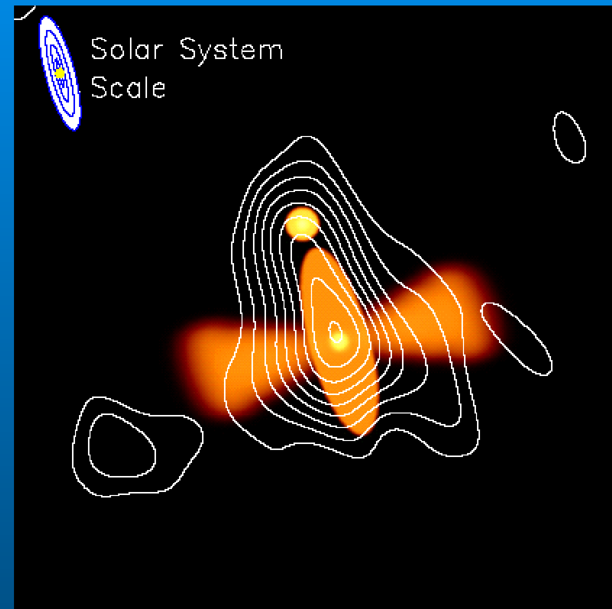
Red=Away from us

S106, IR Subaru Telescope, Japan

Accretion Disk



Credit: B. Starosta, NRAO/AUI/NSF



tours: observations

or: model of accretion disk,
tral star, outflow, & companion
tostar:

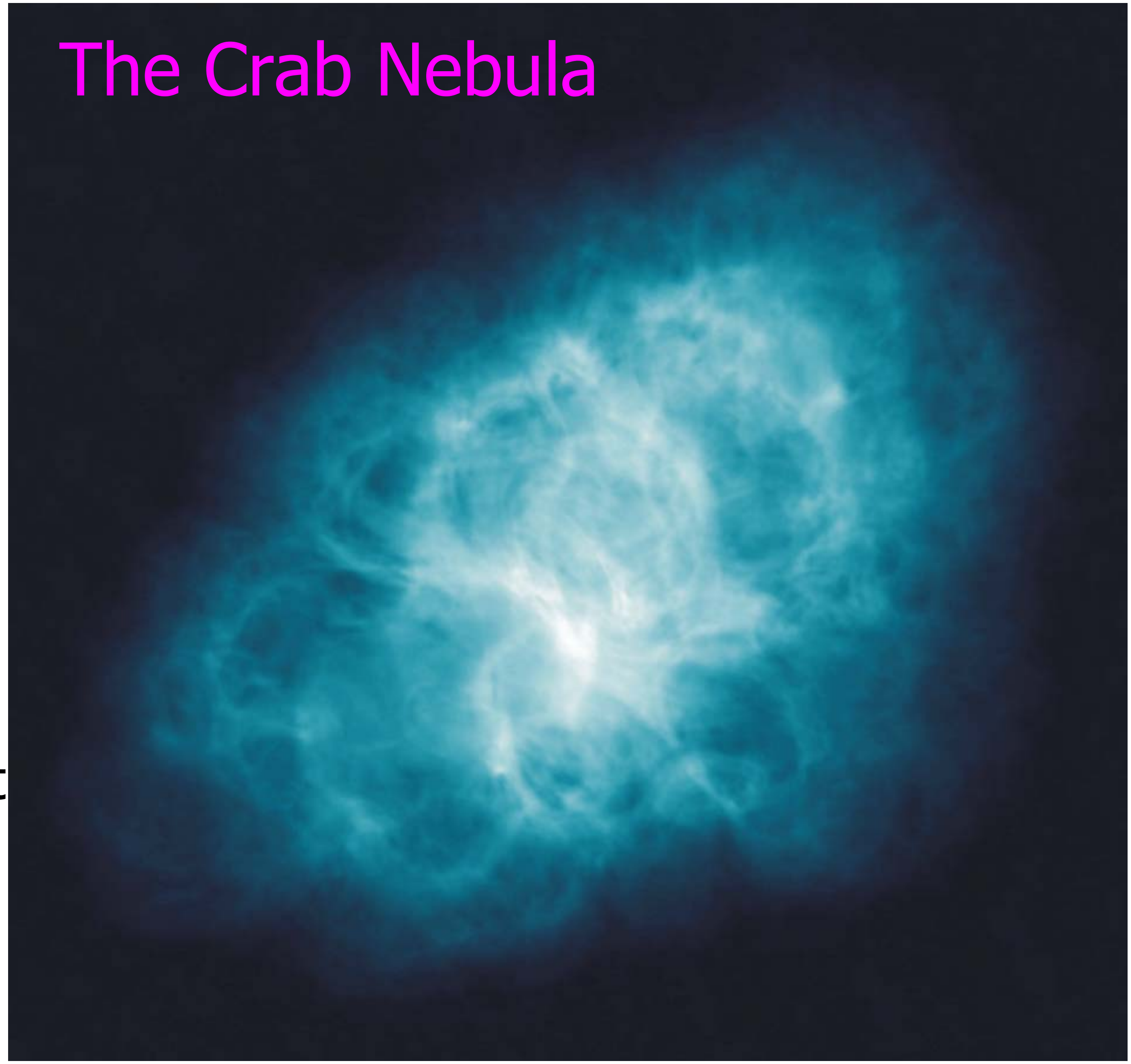
$_{sun}$ protostar

) M_{sun} disk

Outflow with 40° opening angle.

- 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

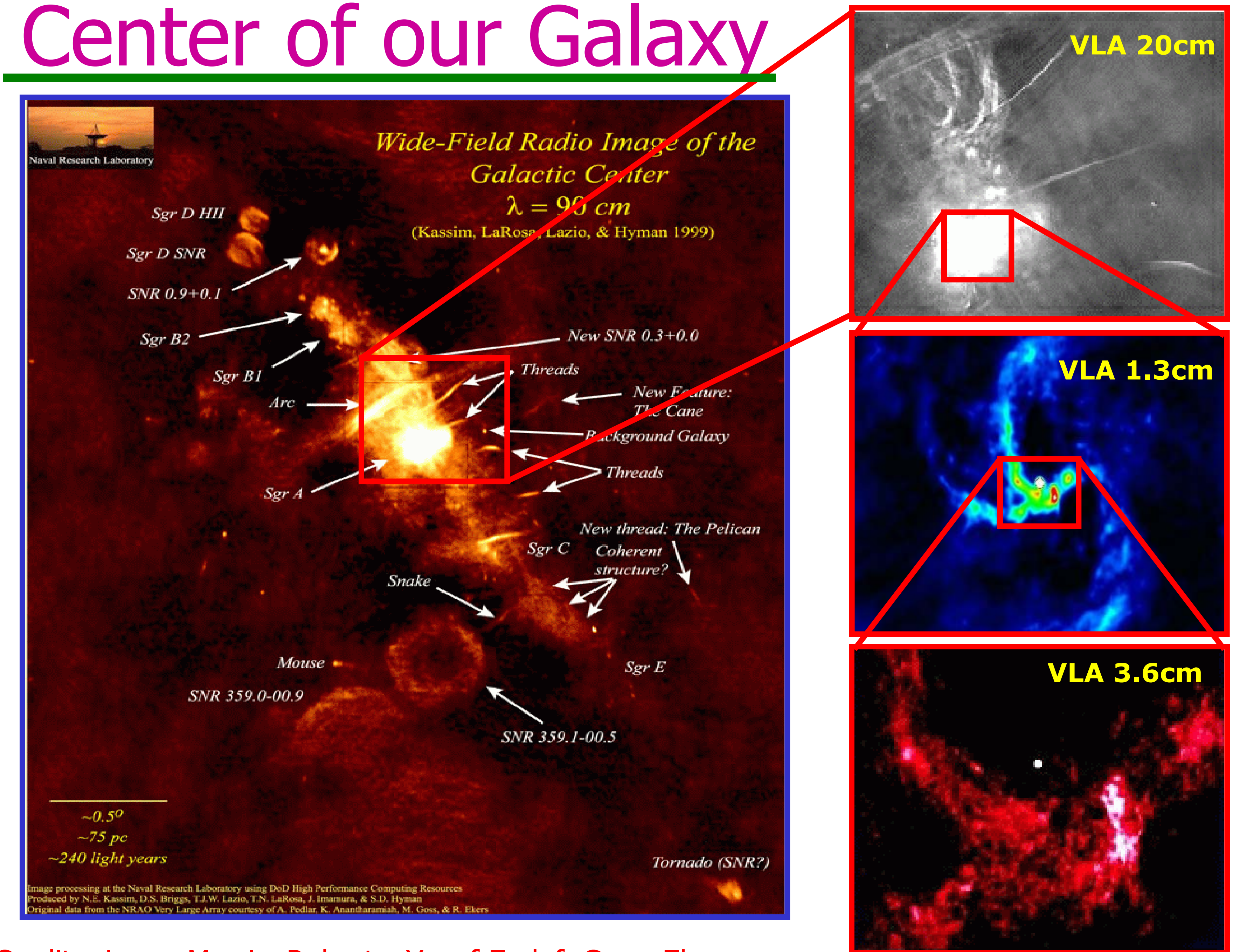
Rudnick et al., Image by T. Rector www.nrao.edu/imagegallery



- 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

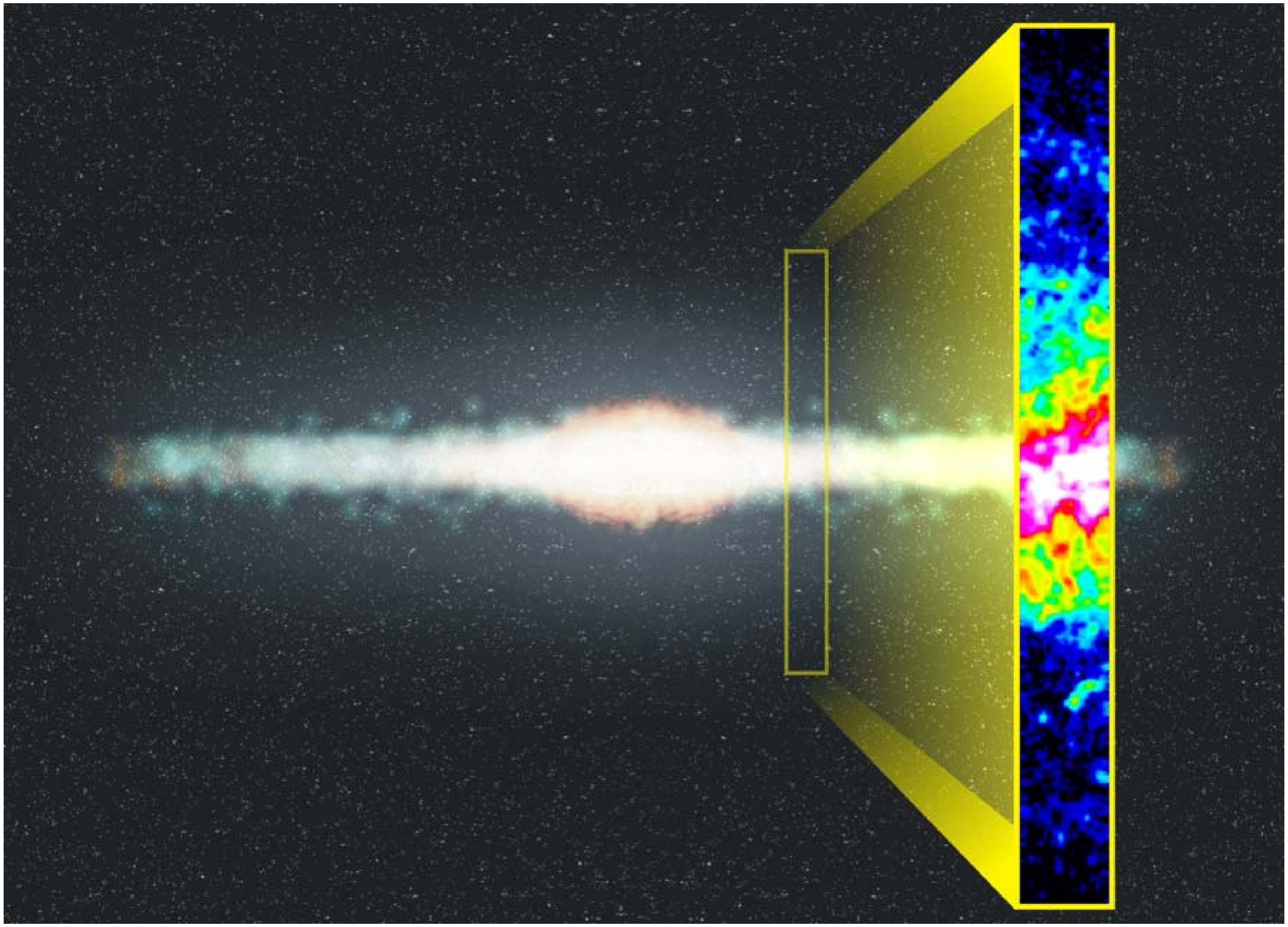
M. Bietenholz
www.nrao.edu/imagegallery

Center of our Galaxy



Credits: Lang, Morris, Roberts, Yusef-Zadef, Goss, Zhao

Same Space -- Different Light



Extragalactic Supernovae

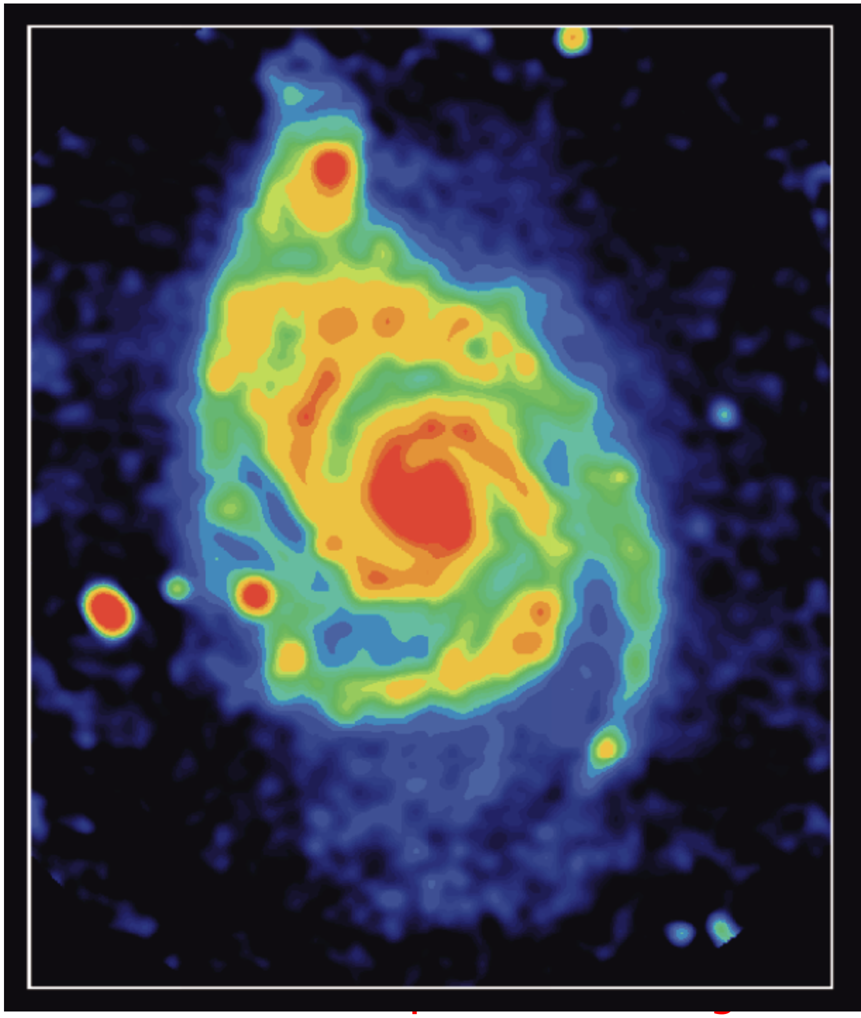
SN 1993J in M81

VLBA Observation from
May 17, 1993 – Feb 25 2000

Bartel, Bietenholz, Rupen et al.

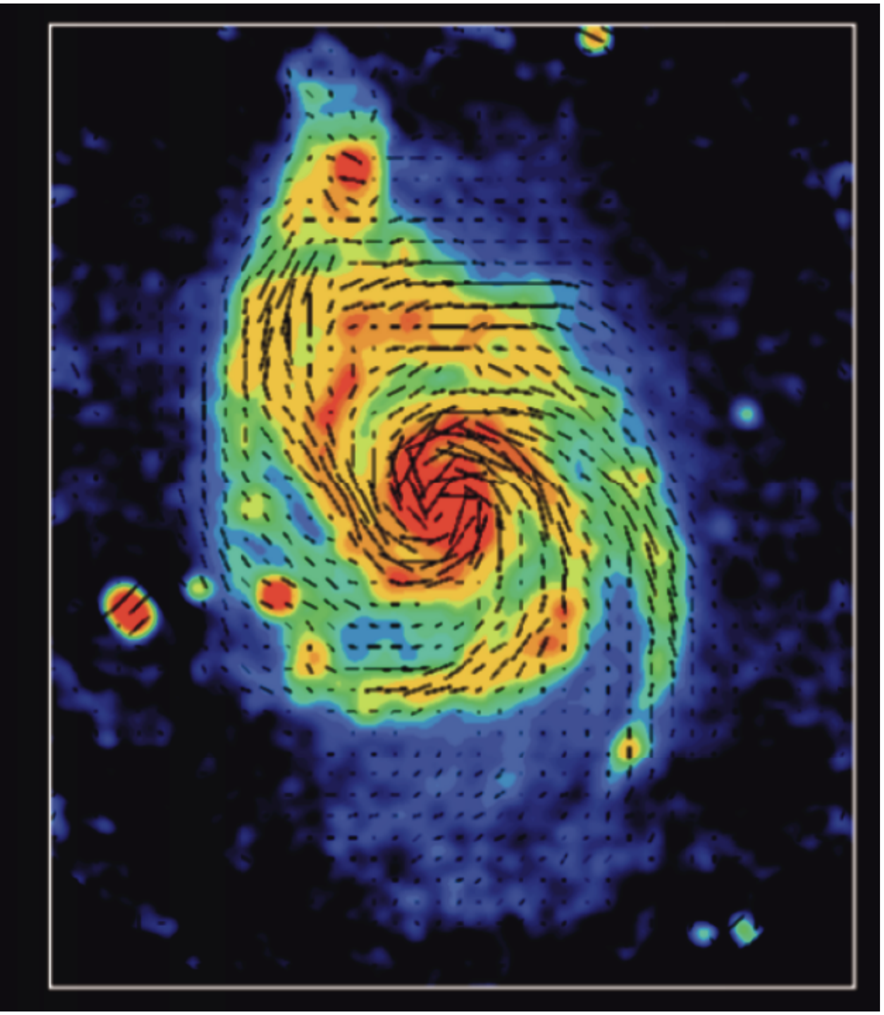
aries.phys.yorku.ca/~bartel/SNmovie.html

Magnetic Field Orientation in Galaxies



Radio Continuum

Beck, Horellou, Neininger

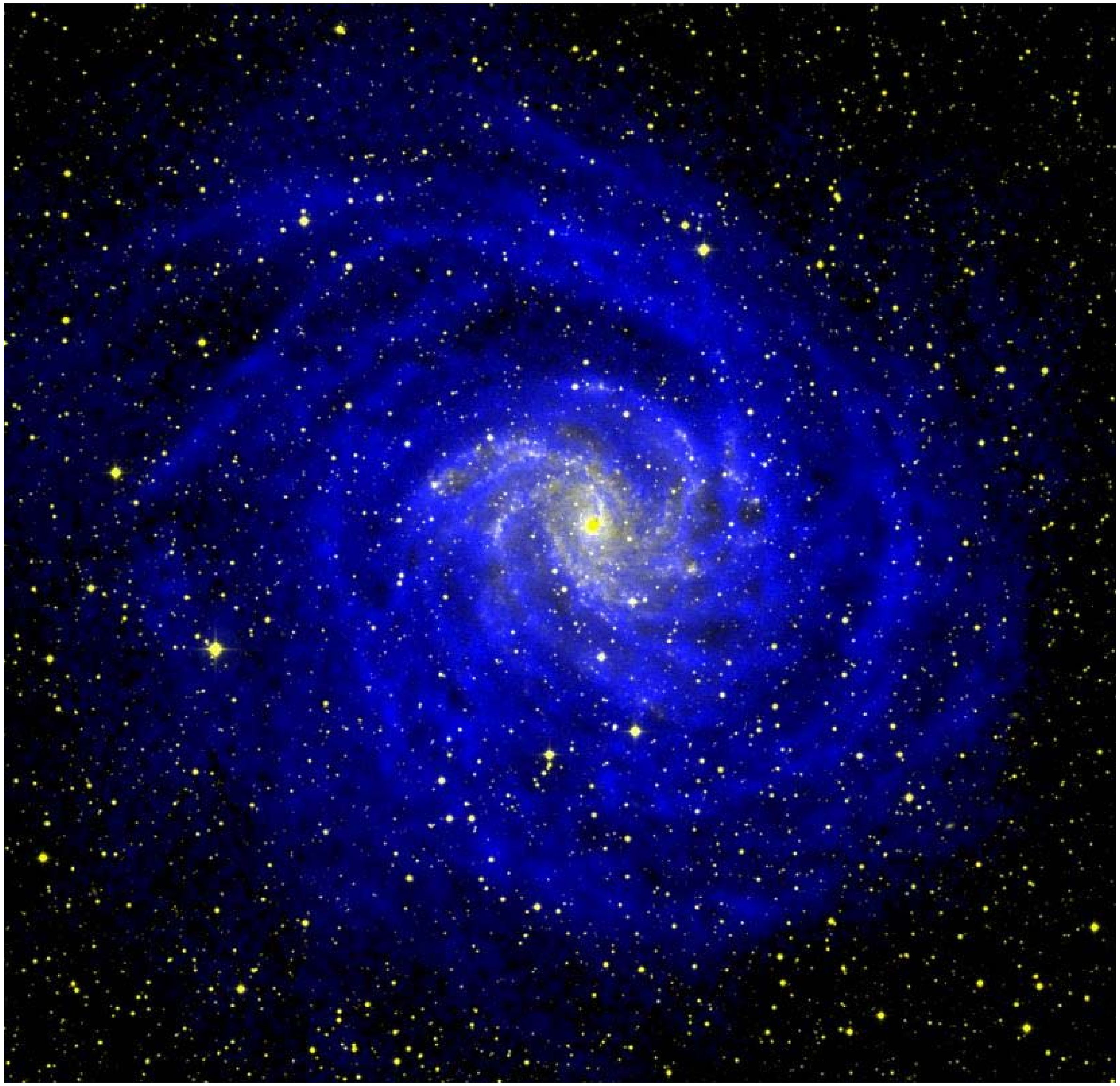


Lines=Magnetic Field Orientation

www.nrao.edu/imagegallery

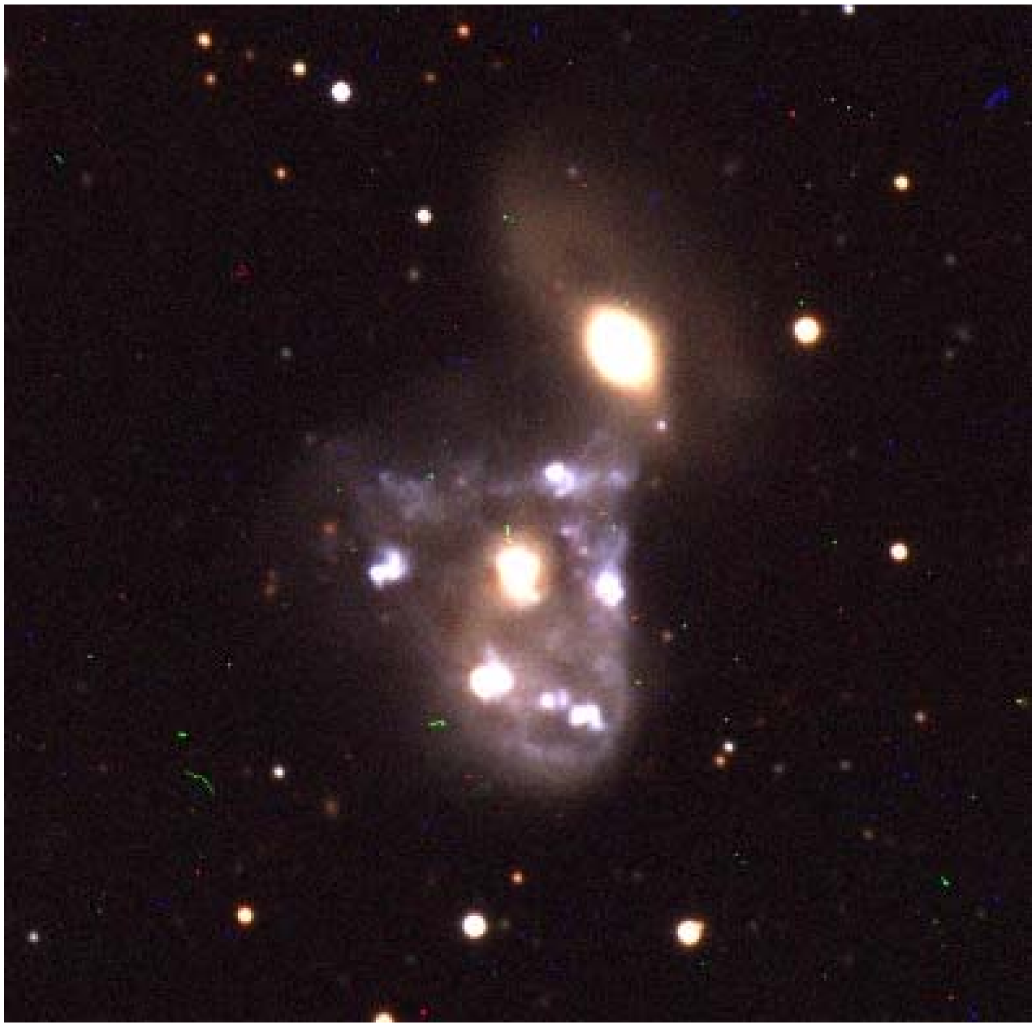
Neutral Hydrogen in Galaxies

- 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

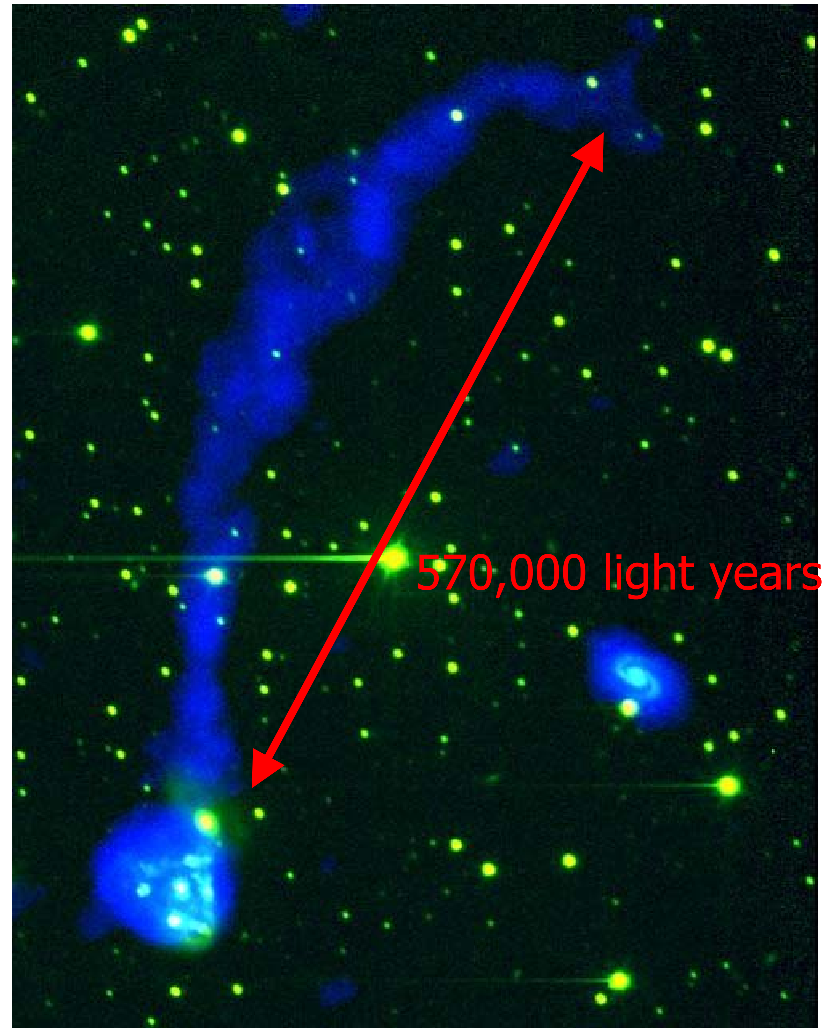


21 cm Spectral Line Observations

Often find things you'd never guess from optical light



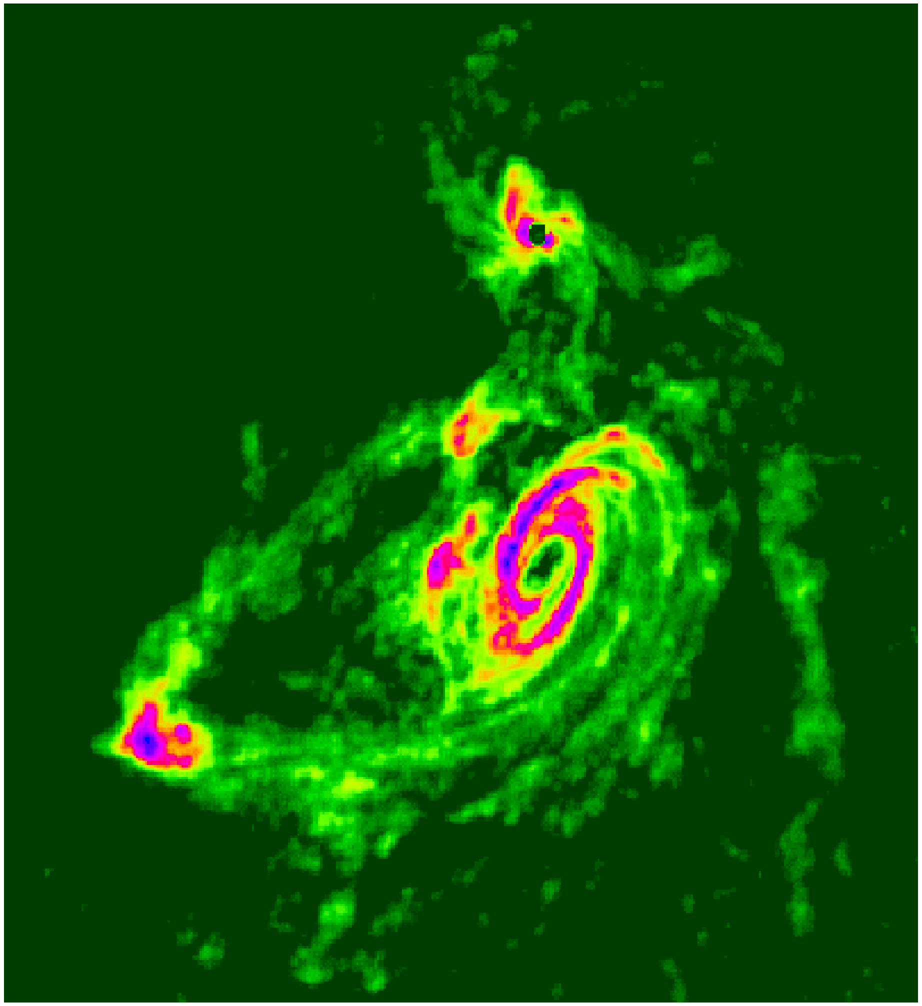
Optical Image of Ring Galaxy Arp 143



VLA 21cm observation Appleton et al. 1987

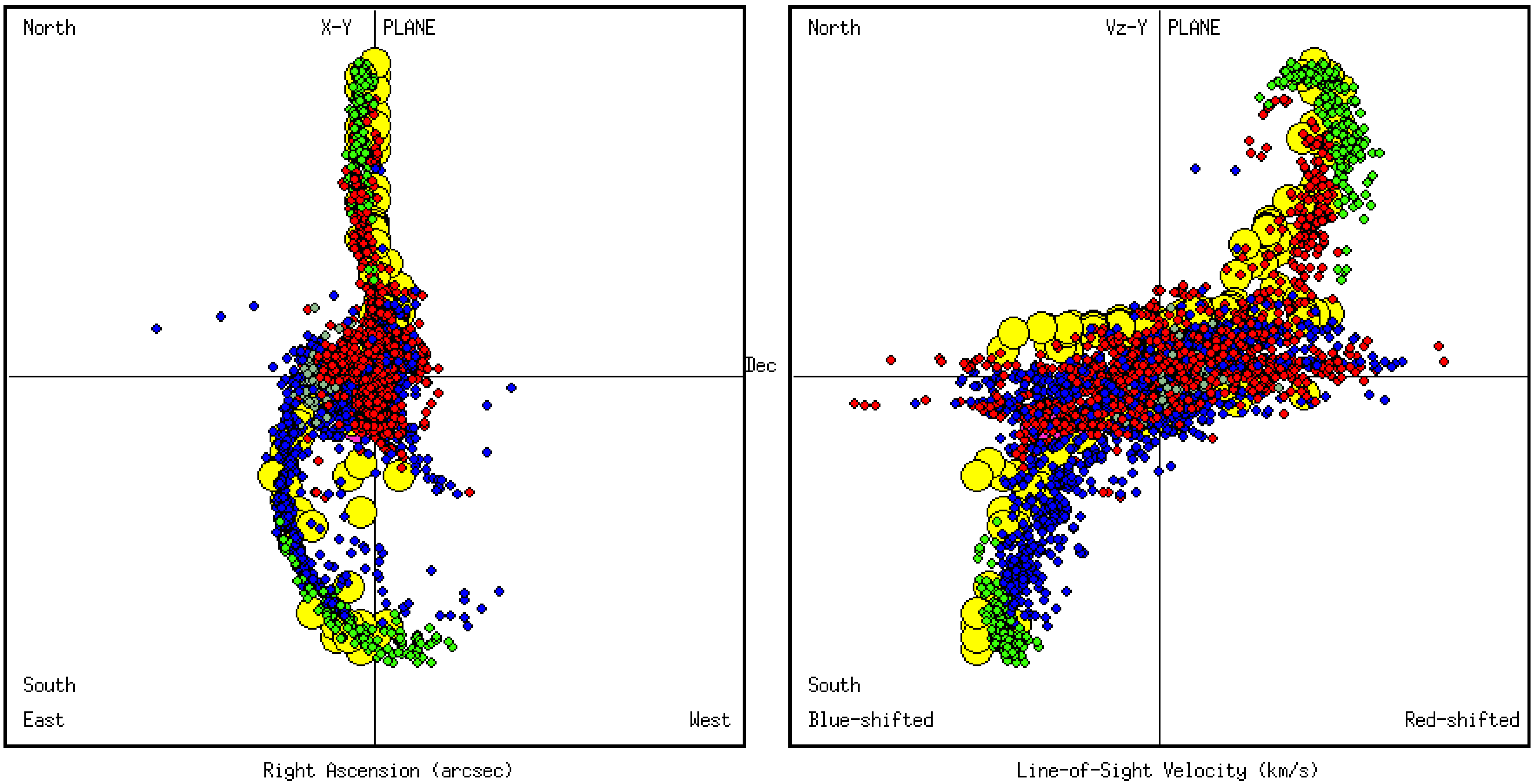
21 cm Spectral Line Observations

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

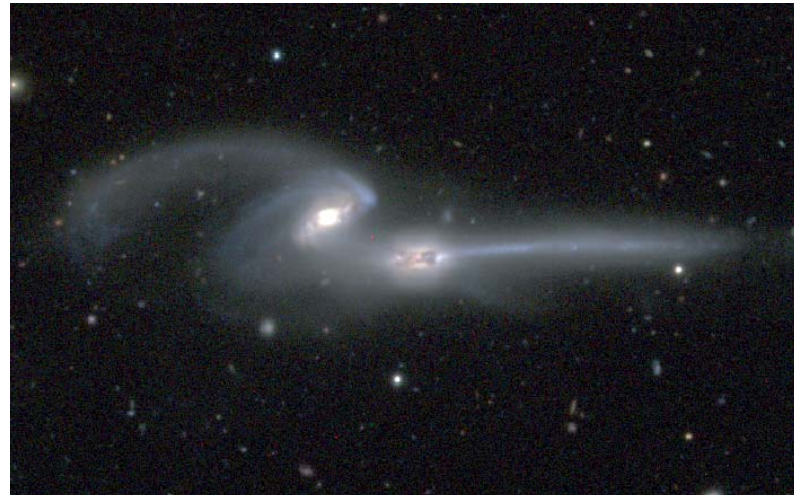


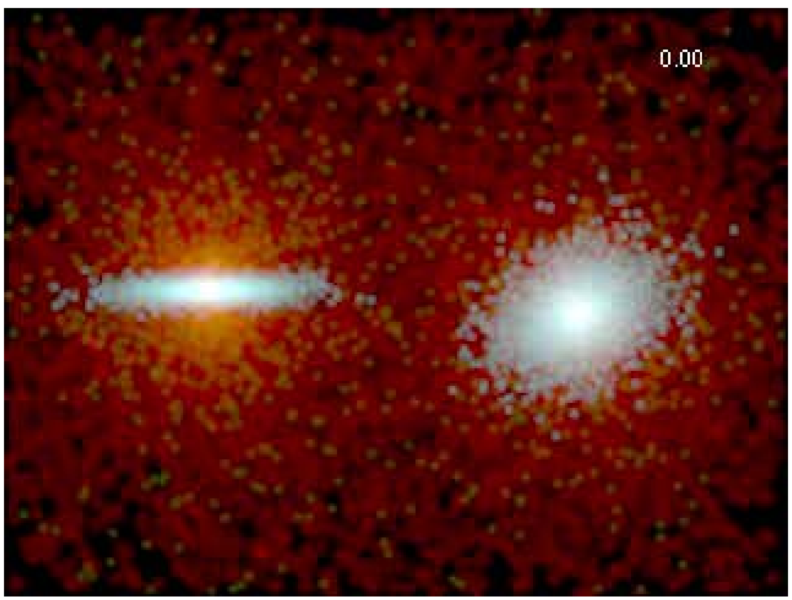
Spatial and Velocity information help motivate physical models

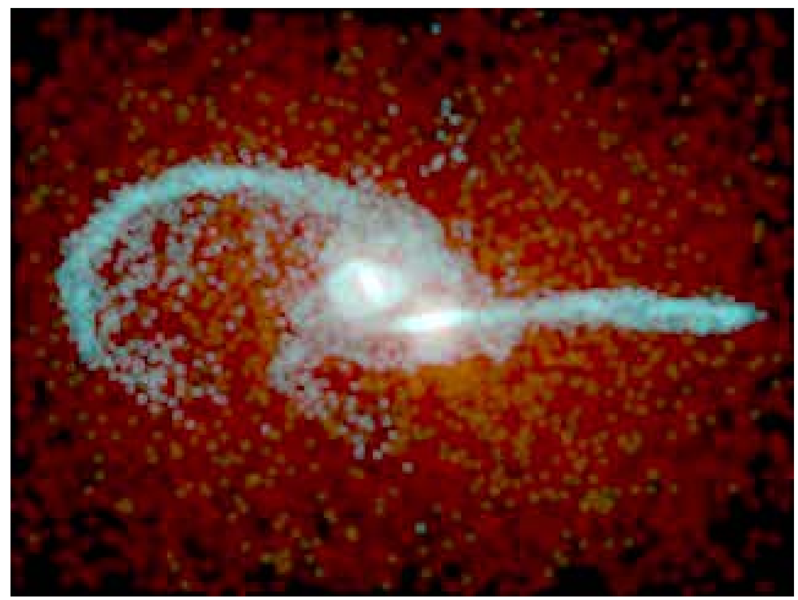
N-body simulation of NGC 4676 "The Mice" Hibbard & Barnes, in preparation

N-body simulations provide past/future evolution and 3-D geometry

N-body simulation of NGC 4676 “The Mice”
Hibbard & Barnes, in preparation

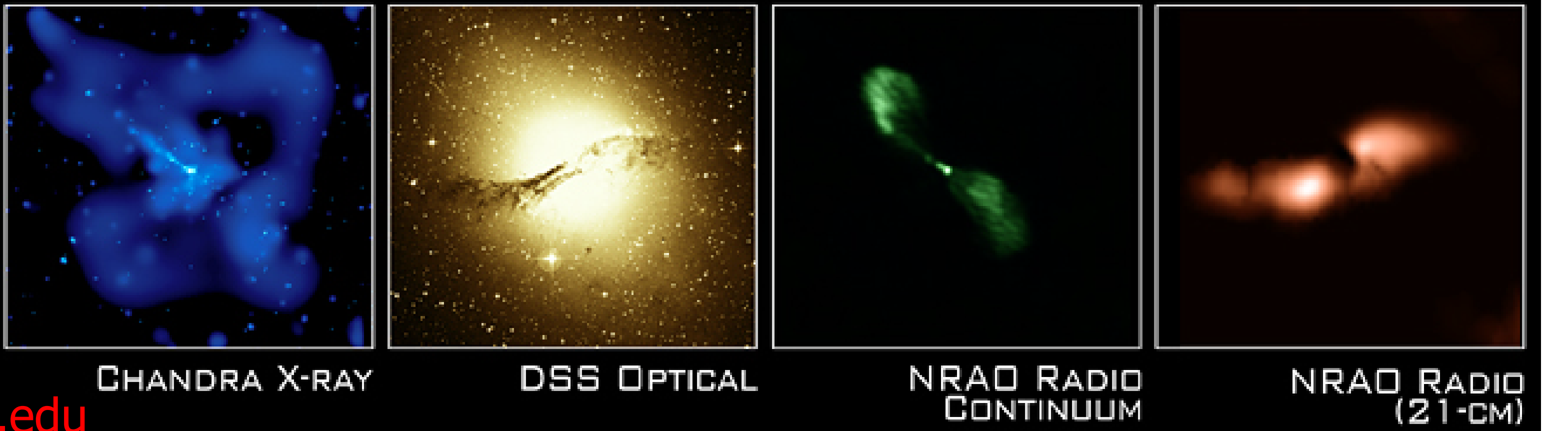






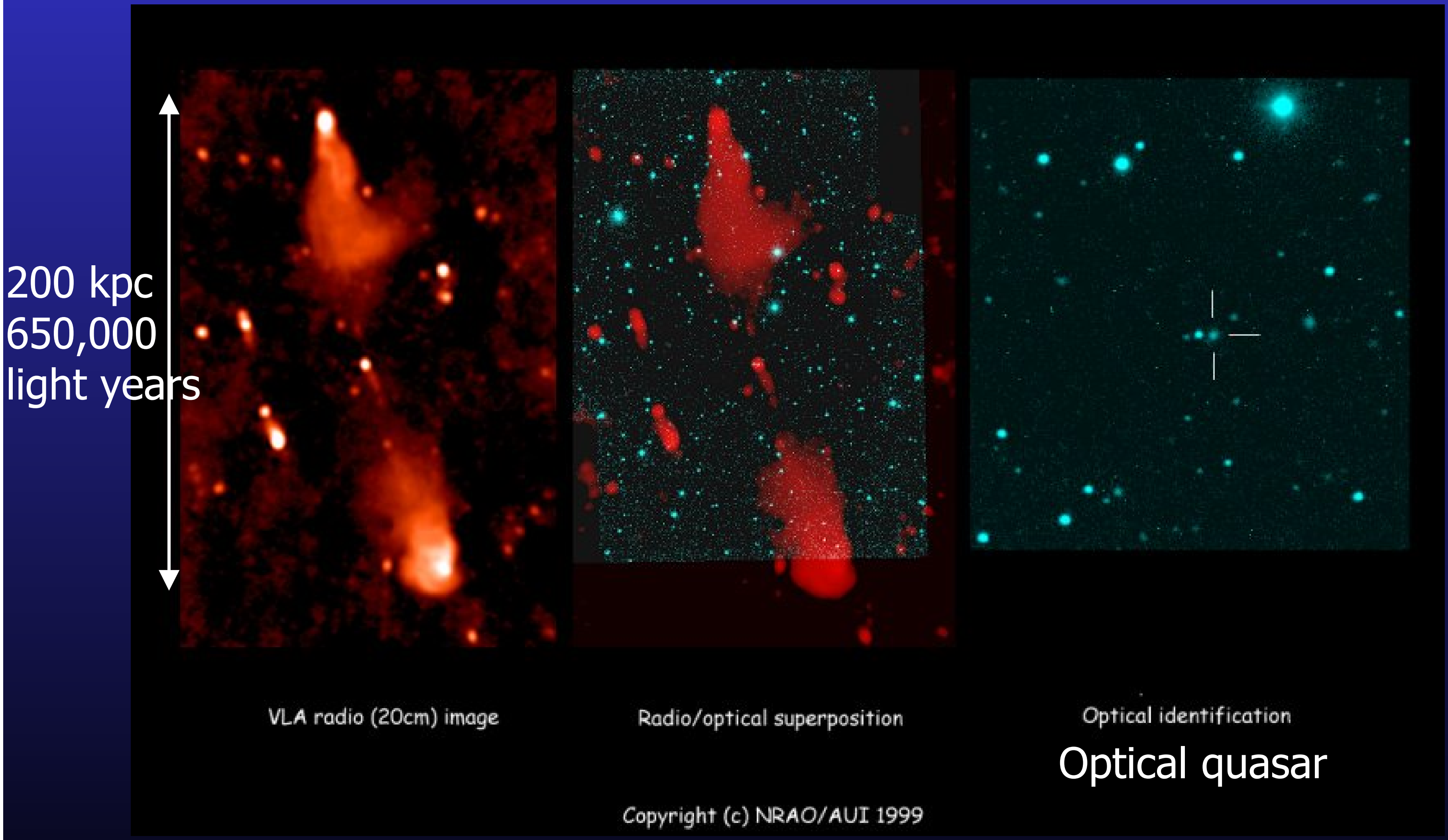
Information from Radio compliments that from other wavelengths

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



Chandra.harvard.edu

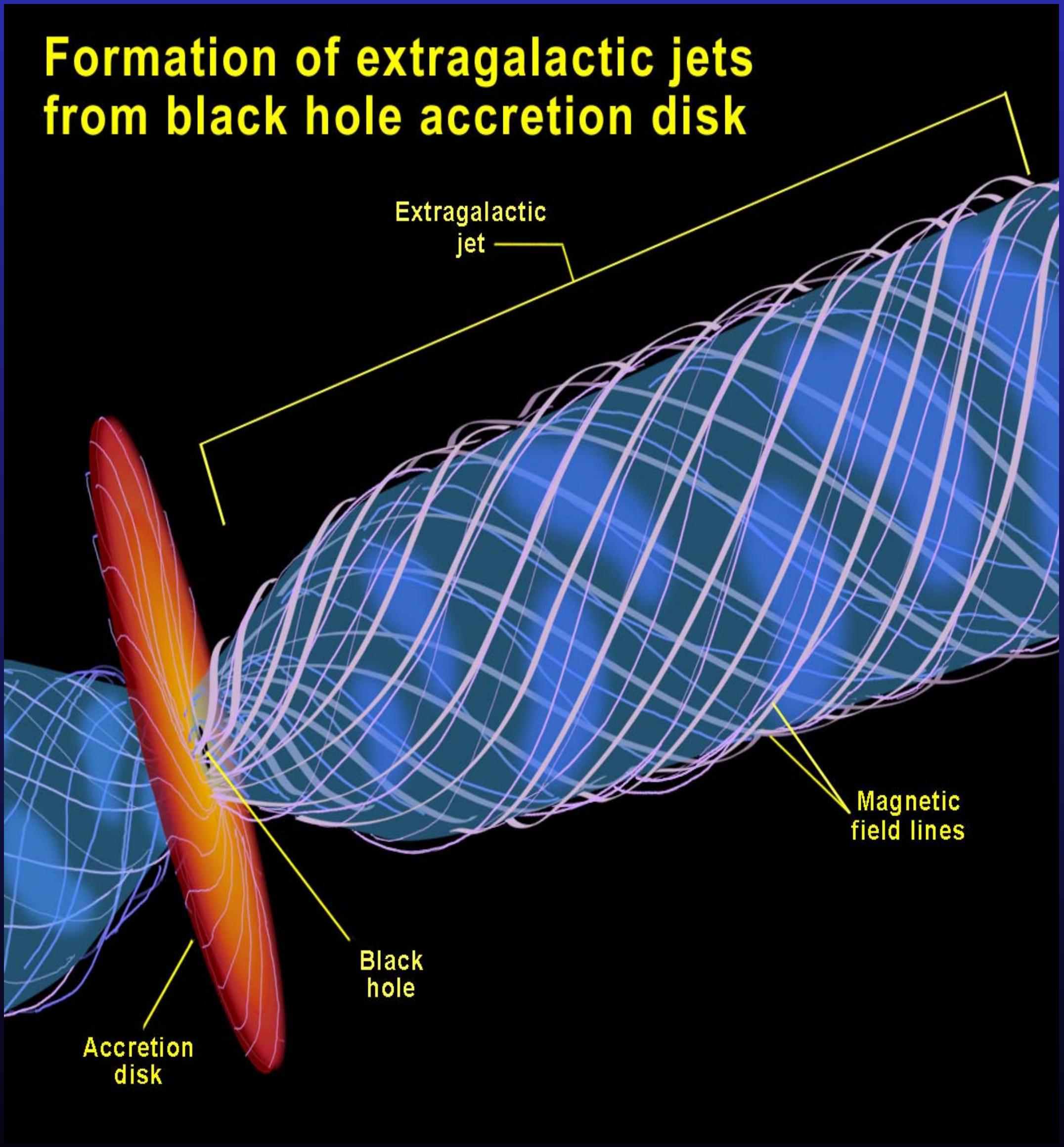
Radio Jets



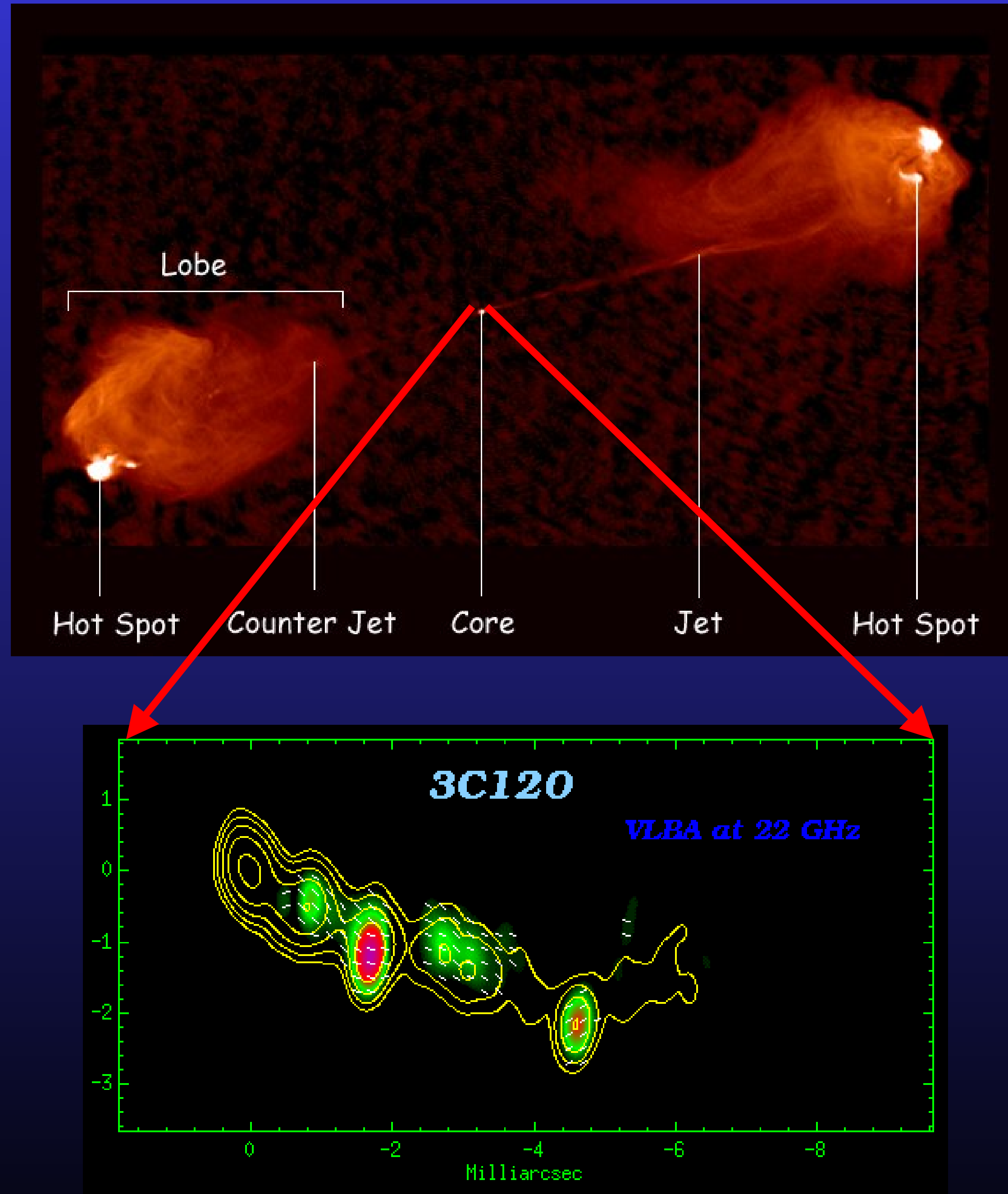
An exclusively radio phenomena

Jet Mechanism:

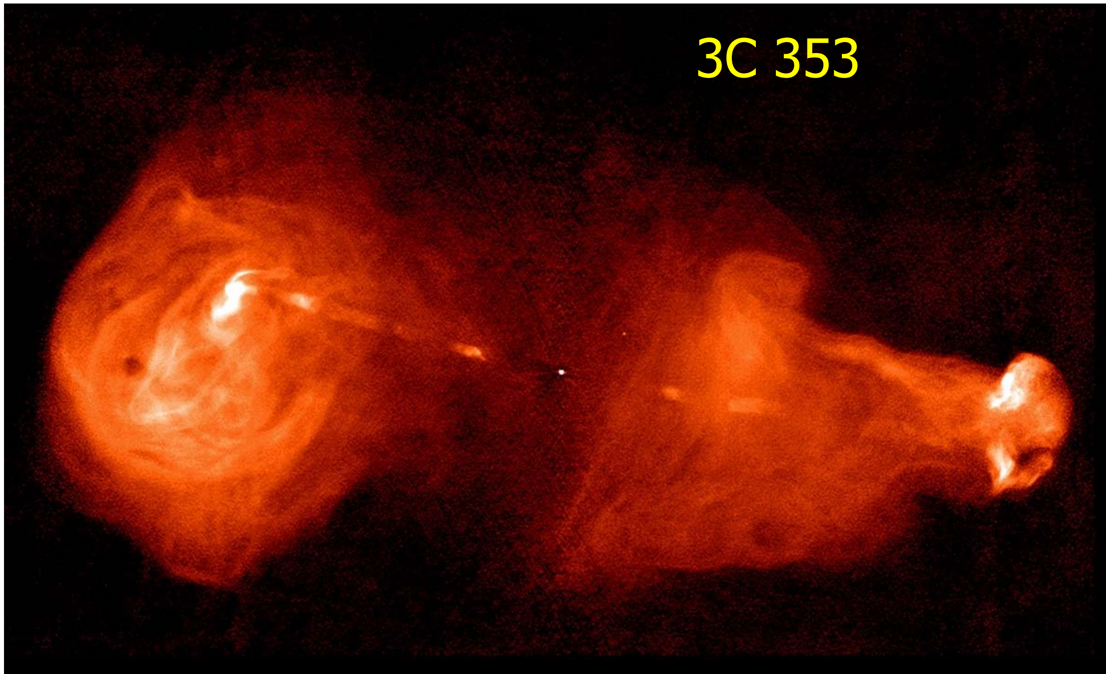
- Accretion of gas onto a massive central black hole releases tremendous amounts of energy
- Magnetic field collimates outflow and accelerates particles to close to the speed of light

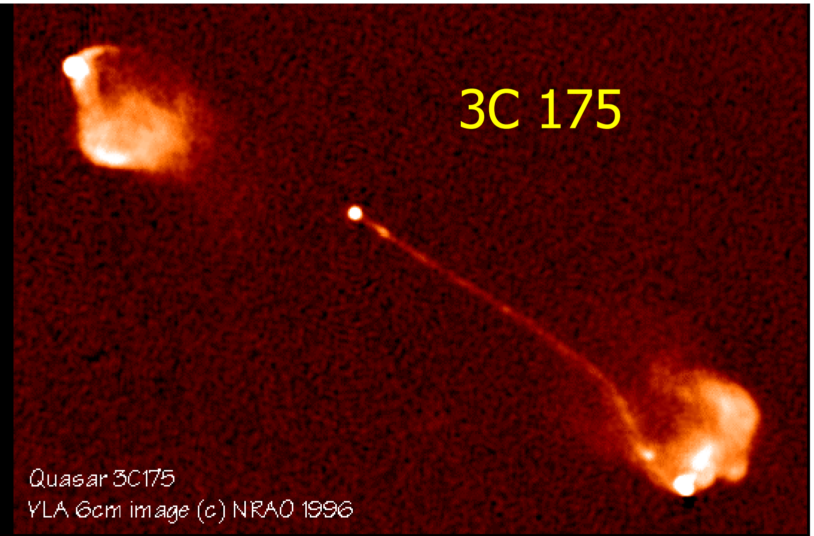


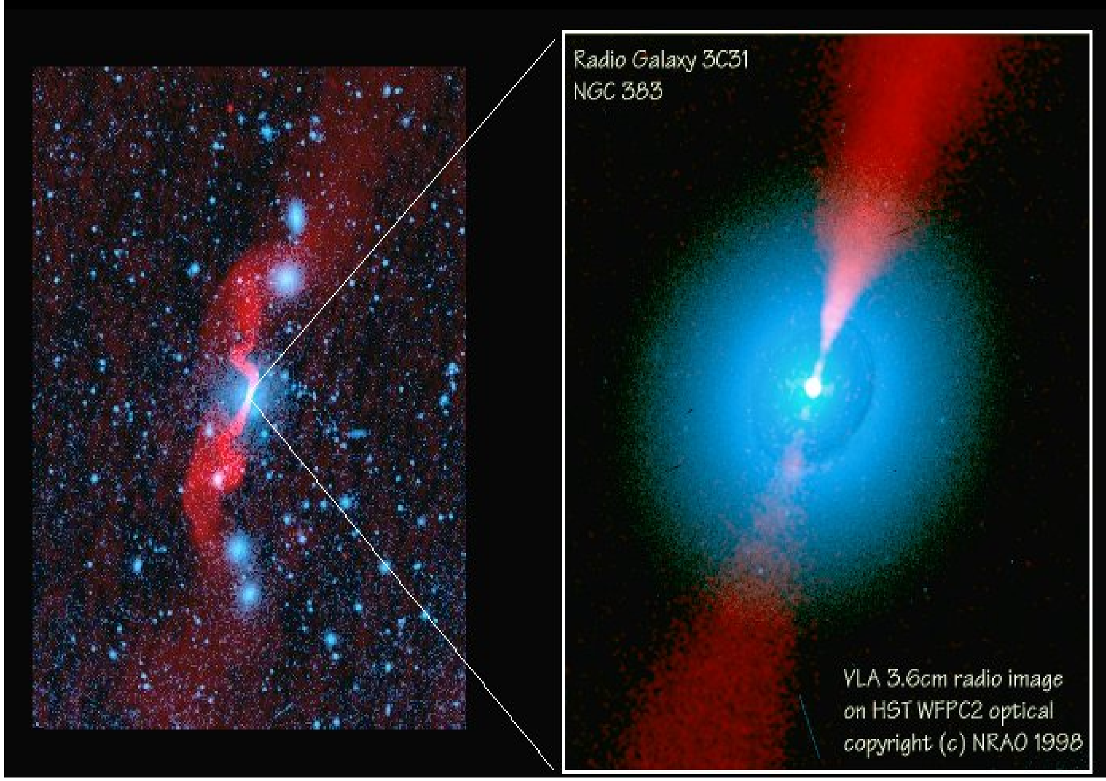
VLBA Time-Elapsed Observations of the Innermost Regions of a Jet

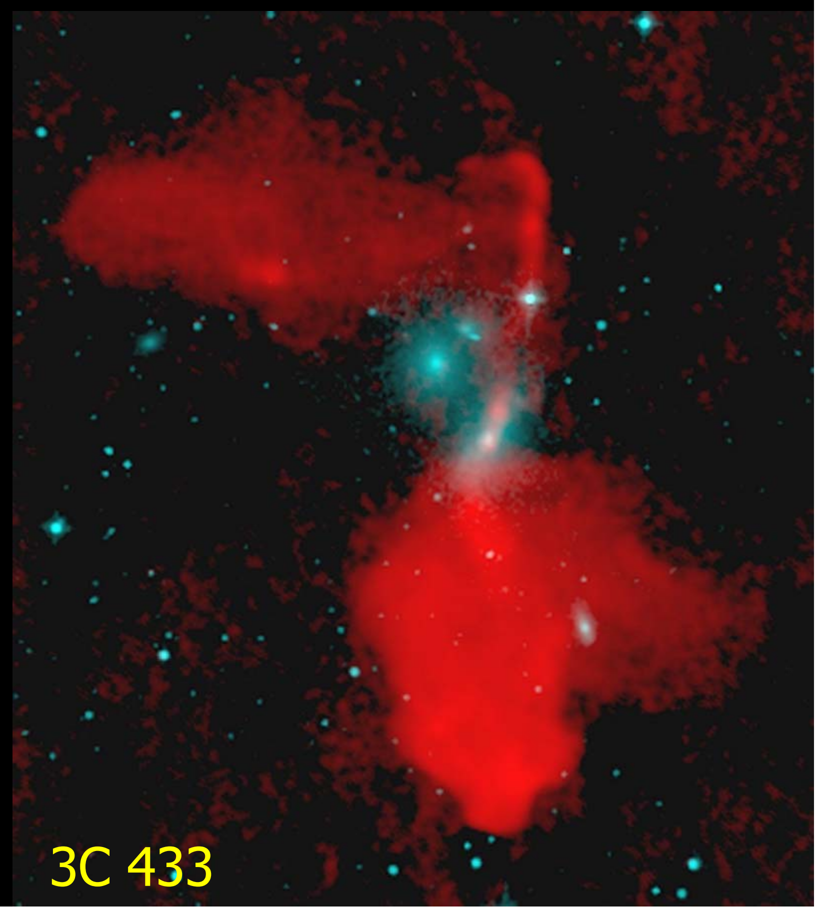


AGN Artistic Simulation by Steffen & Gomez


3C 353

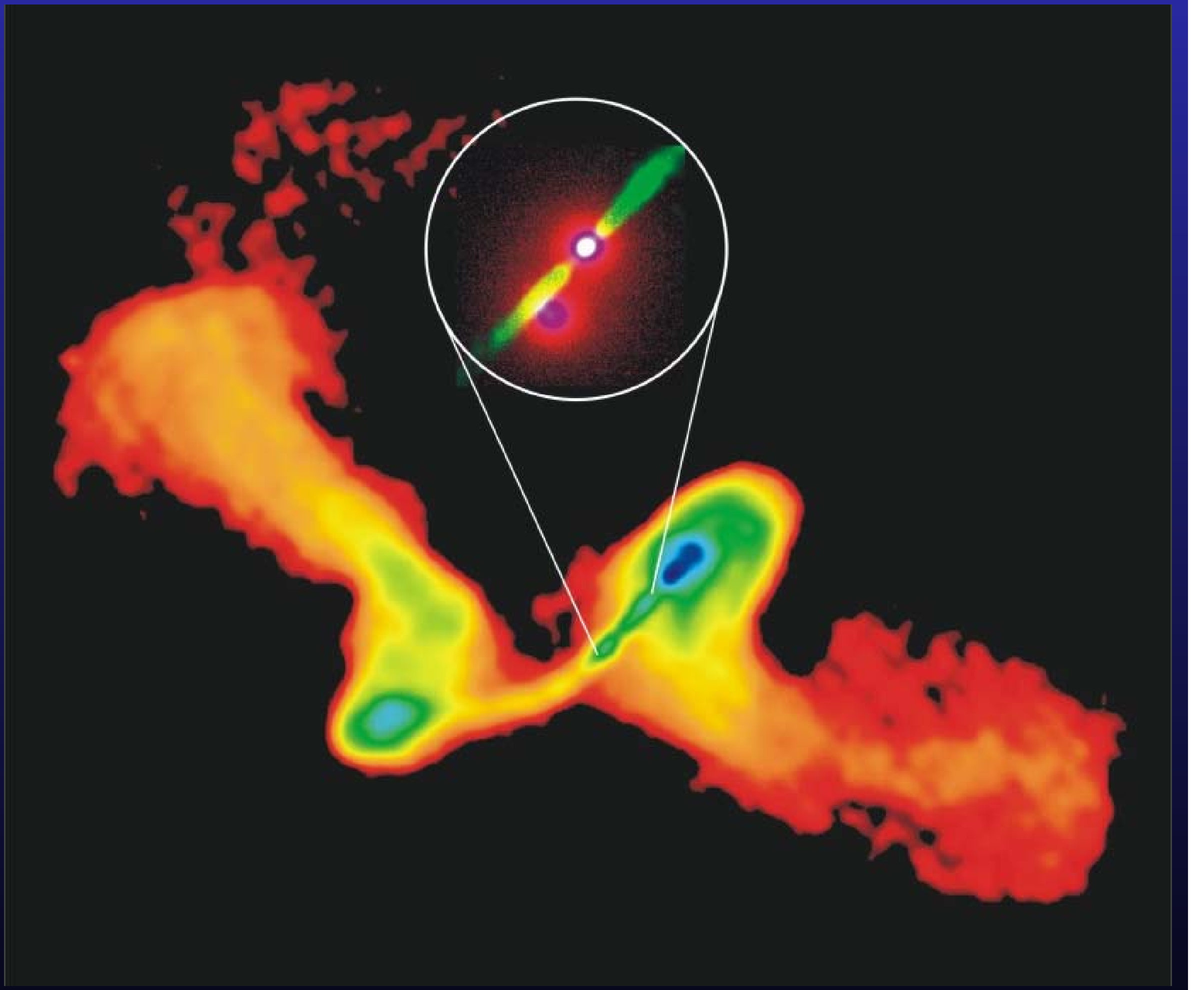

3C 175
Quasar 3C175
VLA 6cm image (c) NRAO 1996


Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998


3C 433

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

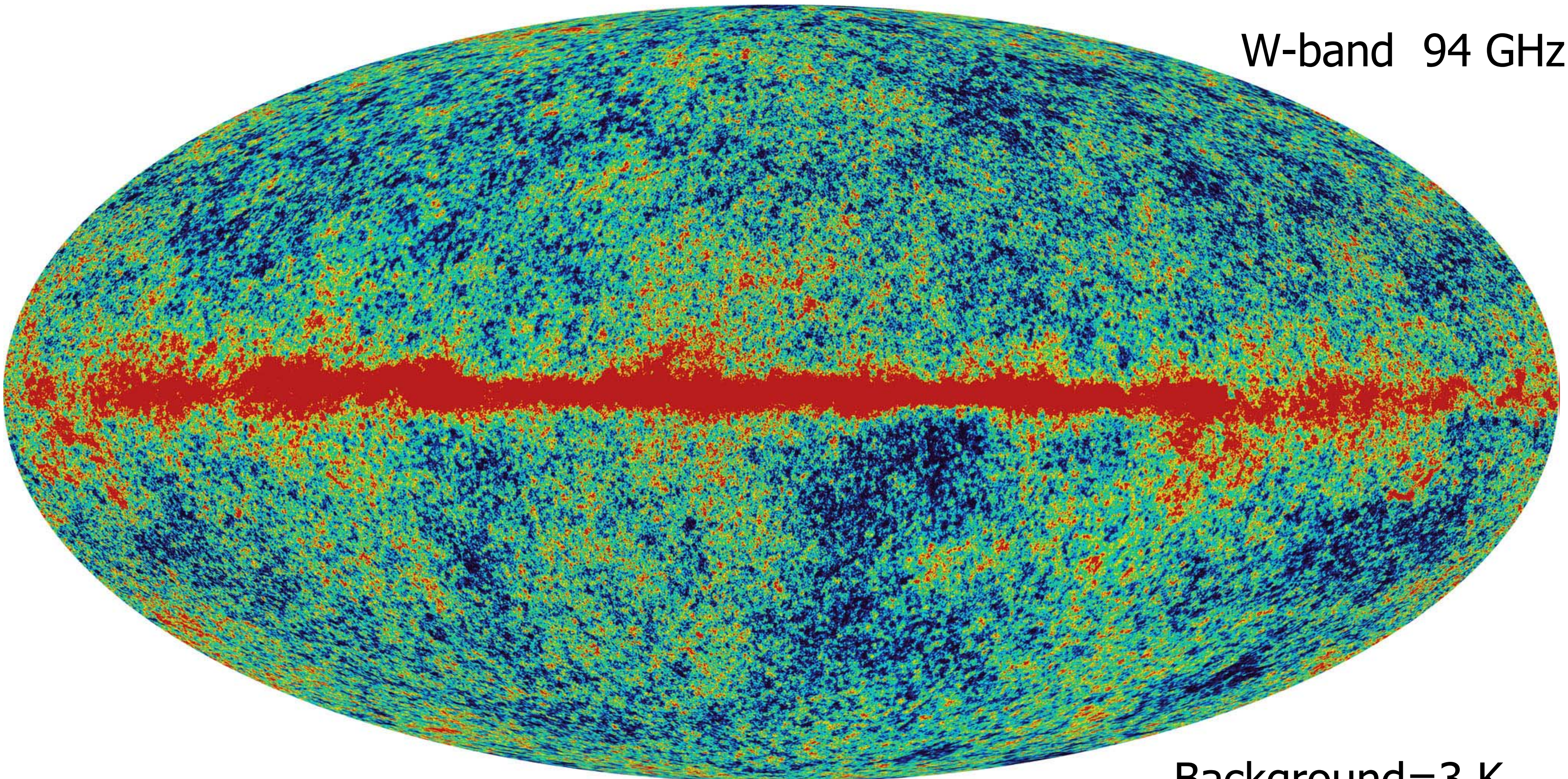


Merritt & Ekers   www.nrao.edu/imagegallery

Wilkinson Microwave Anisotropy Probe (WMAP)

map.gsfc.nasa.gov

W-band 94 GHz



Background=3 K blackbody radiation

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 to as low as 300 MHz.

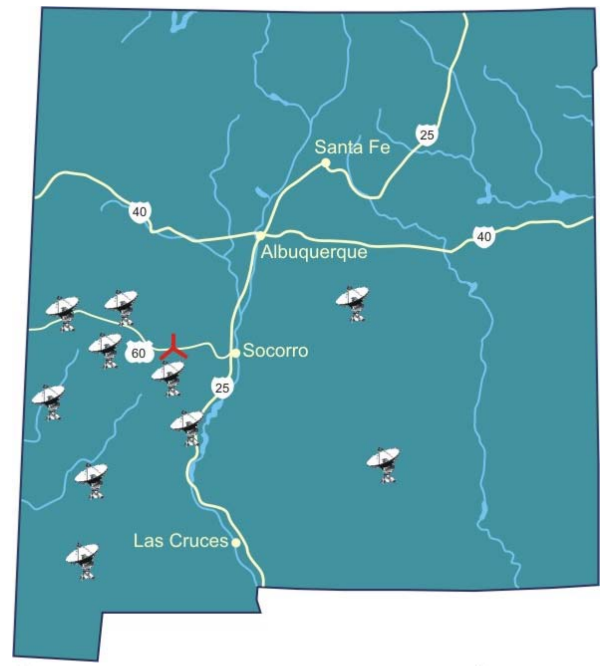
Spectral Capabilities:
As many as 262,144 frequency channels will provide flexible, variable resolutions between 1 MHz and 1 Hz.

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 exisiting 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.

Atacama Large Millimeter Array

A project of the National Science Foundation and the National Research Foundation of Canada through the North American Project for Radio Astronomy via its partners, Associated Universities, Inc. operating the National Radio Astronomy Observatory, and the Herzberg Institute of Astronomy and the European Southern Observatory and its partners The Centre lational de la Recherche Scientifique (CNRS), France; Max Planck Gesellschaft (MPG), Germany; The Netherlands Foundation for Research in Astronomy, (NFRA); Nederlandse Onderzoekschool Voor Astronomie, (NOVA); The United Kingdom Particle Physics and Astronomy Research Council, (PPARC);The Swedish Natural Science Research Council, (NFR); and the Ministry de Ciencia y Tecnologia and Instituto Geografico Nacional (IGN,)(Spain)

- 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.

Al Wootten, ALMA/US Project Scientist

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

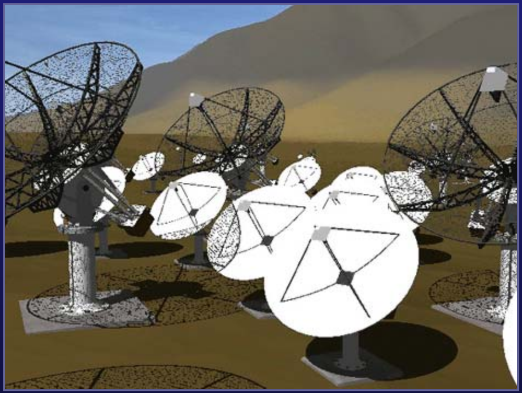
www.seti-inst.edu/seti/our_projects

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