



## Radio Astronomy Intro, part 1

Greg Taylor University of New Mexico

Astronomy 423/539 at UNM Radio Astronomy



### **Course Goals**

- To understand how radio astronomical instrumentation functions and is used in practice.
- To understand some of the exciting science carried out at radio wavelengths.
- To understand the main astrophysical processes which give rise to radio emission
- A chance to see and work with real radio data from the Very Large Array, the Very Long Baseline Array, and the Long Wavelength Array
- Your goals?





### **Course Outline**

- Exploring the Invisible Universe
- Some basic information (radiative transfer, thermal emission, the radiometry equation)
- Signals and noise, receivers
- Antennas Our Connection to the Universe
- The Two-Element Interferometer
- Aperture Synthesis techniques
  - Connected element interferometers (VLA)
  - Very Long Baseline Interferometry (VLBA)
  - Long Wavelength Interferometry (LWA)
- Synchrotron Emission and Magnetic Fields
- Active Galactic Nuclei and their Jets
- See the <u>Syllabus</u> for more details
- TA: Dustin Edgeman



### **Course Methods**

- Materials will be posted at: http://leo.phys.unm.edu/~gbtaylor/astr423/
- Weekly homework assignments
- Reading assignments (2 books, both available from me)
- Lectures
  - Powerpoint slides (will be posted)
  - Traditional chalkboard lectures (not posted)
  - data reduction tutorials (~1 or 2, not posted)
- Two mid-term exams, no final exam
- Observing projects with the LWA (schedules by Feb 17 !)
- A day at the VLA/LWA touring (TBD)
- Homework analyzing VLA data and LWA data
- Written and oral reports based on observations
- Grad students will be expected to do some extra work (lead group, schedule observations, etc.)





#### How to Use a Radio Telescope

- 1. Come up with a great idea
- 2. Write a compelling proposal
- 3. Submit your great proposal for review
- 4. Wait a while
- 5. Schedule the observations
- 6. Watch the observations take place
- 7. Calibrate the data
- 8. Make images and perform detailed analysis
- 9. Write up your results and submit them for publication



#### How we will use the LWA

- 1. Come up with a great idea (start thinking about this now!)
- 2. Write a compelling proposal (<300 words; Homework #1)
- 3. Submit your great proposal for review (proposals due Feb 3)
- 4. Wait a while (TAC decision on Feb 8; LWA observing time allocated)
- 5. Schedule the observations (by Feb 17)
- 6. Watch the observations take place https://lwalab.phys.unm.edu/OpScreen/index.html
- 7. Calibrate the data (homework & project)
- 8. Make images and perform detailed analysis (homework & project)
- 9. Write up your results and submit them for publication (for a grade)



#### How we will use the LWA

1. We have  $\sim 50$  hours of LWA time available

### 2. We will have a class homework observing pulsars

- 1. Take some data and practice RFI excision techniques
- 2. Learn how to do a dispersion/period search
- 3. Discover new aspects of pulsars at long wavelengths!





### **Observing Constraints**

- LWA time can be at any LST, DEC > -10:00:00
- LWA observations can be:
  - All sky using TBN/TBF/TBW
  - Pointed observations with a beam using one or more stations
  - Interferometry mode using the 3 New Mexico stations
- LWA Frequency range 5-88 MHz
- Example projects:

https://leo.phys.unm.edu/~lwa/obssched.html

• Publications:

https://leo.phys.unm.edu/~lwa/publ.html





UNM Center for Astrophysics Research and Technologies seminar series Thursdays @ 2pm in PAIS 3205 next talk Jan 23: Kyle Massingill ... on "Tropospheric Phase Correction Using Water Vapor Radiometers"

### UNM Colloquium Series Fridays @ 3:30pm in PAIS 1100







## The LWA Radio Observatory Staff



Grads	Students	Undergrads
Logan Cordonnier		Sara Pezzaioli
Ella Hort Evan Sheldahl		
Charlie Siders		
Craig Taylor		

Faculty and Staff Greg Taylor (UNM) Jayce Dowell (UNM) Joaquin Verastegui (UNM) Sarah Chastain (UNM) Ken Obenberger (AFRL/UNM) Frank Schinzel (NSF/UNM)

2017-10-25 19:17:11 UTC



# The first station of Long Wavelength Array (LWA 1)

- Operating frequency 10 – 88 MHz
- 256 dual- polarization dipole antennas
- Distributed within a 100 × 110m ellipse
- Co-located with the Very Large Array (VLA)
- Two operating modes: Digital beamforming and All Sky



# PASI All sky mode

- Primary beam of single dipole is sensitive to whole sky
- Continuous collection of voltage time series
- 75 kHz bandwidth with 6 channels



# LWA All Sky Imager (Orville SV+NA)

- 20 MHz bandwidth with 100 kHz channels
- Fourier transform and correlates the voltage series in real time to get visibilities every 5 s
- Visibilities are converted to images of the sky
- The images are uploaded to LWA TV
- Movies for each day archived



http://www.phys.unm.edu/~lwa/lwatv.html

# **Emission from Jupiter**



#### NASA 1604 - Exoplanets



# **Beamforming - DRX**

- Delay and sum beamforming
- Up to 4 beams
- 2 tunings of 20 MHz, dual pol
- Raw voltage time series or spectrometer mode





 Pulsars as probes of Solar system and Interstellar Medium

 Dispersion Measure
 Scattering
 Rotation Measure

Gravitational Waves



### NASA 1627 – Heliophysics NASA 1607 – Gravitational Waves

Kumar et al. 2023

Two New Mini stations funded by AFOSR/DURIP: Texas Tech – PI Tom Maccarone ASU – PI Judd Bowman





The FULL Electromagnetic Spectrum



## **EM Radiation – basic properties**

• speed of light =  $c = \lambda v$  $c = constant = 3 \times 10^{10} cm/s = 3 \times 10^{5} km/s$ 

 $\lambda$  has units of length (cm) - we will use c.g.s. units (mostly) v has units of 1/s (Hz)

# • Photons carry energy depending on their frequency (or wavelength) E=hv

h = 6.63 x 10<sup>-27</sup> erg s, v is frequency, E energy h = 4.14 x 10<sup>-15</sup> eV s

• note: "high energy" astronomers (X-ray, Gamma Ray) usually use the corresponding energy rather than wavelength, i.e., 10 keV, 2 GeV For example:  $10^{17}$  Hz = 0.4 keV













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## Radio High frequency cut off

- due to the troposphere layers

- H<sub>2</sub>O, O<sub>2</sub> absorb incoming "high frequency" radio photons
- particularly bad spectral windows include:  $H_2O$  at 22.2 GHz (1.35 cm) 183 GHz (1.63 mm)  $O_2$  at 60 GHz (5 mm) 119 GHz (2.52 mm)

water/oxygen "band" features are closely spaced absorption lines
high frequencies good for molecular tines



### Magnetosphere:

free protons & electrons, concentrated in Van Allen Radiation Belt(s)

#### Exosphere: free helium atoms

### Thermosphere:

free electrons concentrated in lonosphere (aurorae)

### Mesosphere: trace dust Stratosphere:

concentration of Ozone and Sulphides in Ozone Layer

### Troposphere:

holds 75% of gaseous mass, including nearly ALL water, particulates, and WEATHER





### **The Very Large Array**

In January the VLA is in A config.



Angular resolution ~ 0.3" at 5 GHz, sensitivity = 13 microJy/beam in 10 minutes @ 5 GHz Frequency range: 1 to 50 GHz





### High Frequency Observing

Because the main culprit for high frequency radio astronomy is WATER VAPOR in the atmosphere, you <u>can</u> improve your observing conditions! - go to HIGH or DRY locations:



#### Atmospheric Opacity at the VLA and ALMA sites



Transmission of the atmosphere from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

⇒atmosphere little problem for  $\lambda$  > cm (most VLA bands up to 15 GHz) ⇒ some problems from 20 to 50 GHz





### Highest, driest telescope site: (~ 16,400 feet) Atacama desert, Northern Chile

Site of millimeter array telescope: ALMA









### ALMA, now complete





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### 66 ALMA Antennas now at high site.





## Radio Low frequency cut off

- due to the ionospheric layers

- free electrons in the ionosphere start to absorb low frequency radio radiation IF the frequency is LESS than the *plasma frequency* 

 $v_p = 8.97 n_e^{1/2}$ where n<sub>e</sub> is the electron density (cm<sup>-3</sup>) and v<sub>p</sub> is in kHz

-n<sub>e</sub> does depend on solar activity! and day/night, location on Earth

-e.g., at night v=4.5 MHz (66 m) daytime v=11 MHz (27 m)

#### 80,000 Magnetosphere: free protons & electrons, 20,000 concentrated in Van Allen Radiation Belt(s) $\sim 4000$ 2000 Exoenhere: Altitude free helium atoms íkmì ~5% Thermosphere: free electrons concentrated 300 in lonosphere (aurorae) 8 Mesosphere: trace dust 51 Stratosphere: 35 concentration of Ozone and

concentration of Ozone and Sulphides in Ozone Layer

### Troposphere:

holds 75% of gaseous mass, including nearly ALL water, particulates, and WEATHER





Surface

# VLA 50-86 MHz

New 4 band feeds (MJP) 4 meter band: 50-86 MHz All 28 installed by 2019



## ELWA – Discovery of a Pulsar Wind Nebula around B0950+08

Ruan et al. 2020



## Long Wavelength Array (LWA)



Frequency Range: 3-88 MHz First station ("LWA-1") completed April 2011

Second NM station ("LWA-SV" completed July 2017

Third NM station: ("LWA-NA" ministation (64 dipoles July 2024)

2025 LWA-CS and LWA-MC stations under construction



### LWA swarm – 1" resolution

## LWA-SV

#### **Construction 2015**



**Advanced Digital Processor** 





## LWA Swarm Science 25.6 MH 011-12-31 02:37:56 UTC Cas A Tau A Jup Resolving Pulsar Scattering Flare Stars and Exoplanets ELWA 74 MHz Imaging Solar **Bursts** From S. White **Active Galaxies and Clusters** 20 19 RIGHT ASCENSION (J2000)

### **Radio Frequency Interference**



Grote Reber's telescope and Radio Frequency Interference in 1938





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## **Radio Frequency Interference (RFI)**



### The Radio Sky





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### Supernovae



### Cass A Rudnick et al.





### A Young Supernova









### Gamma Ray Bursts

### GRB 970508

- First GRB Afterglow detected in the radio
- Size  $< 10^{19}$  cm (3 lt years)
- absolute position to < 1 mas

Taylor et al 1997

• Distance > 10000 lt years

G970508 (VLBA+Y27+EB) Color: total intensity





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Relative Decl. (mas)

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#### Giant Flare from the Magnetar SGR 1806-20





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### Star forming regions - Orion nebula (M42)









## **Planet Formation in progress**

HL Tau protostar and disk

### Discovery/Origins: Proto-stars, planets, disks Star and planet formation with the VLA

- VLA @  $\lambda \sim$  1cm provides three key capabilities
- 1. Imaging to 40mas resolution
- 2. Dense cores, optically-thick in mm: 'terrestrial planet formation zone' < 10AU
- 3. Sensitive to cm-sized dust grains: pebbles to rocks



L1165: binary aligned in disk plane, perpendicular to outflow  $\Rightarrow$ protostellar *disk fragmentation* 

NGC1333 IRAS2A: double, misaligned outflows  $\Rightarrow$  turbulent fragmentation of dense core during collapse (Tobin et al. 2015)

### Normal Galaxies







3C31

### Active galaxy





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### Cygnus A – prototypical radio galaxy -- FR II







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### Quasar







### **3C279 Quasar with the VLBA**



Wehrle et al. 2001, ApJS, 133, 297





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### M87 Radio Galaxy



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### J12448+4048

### Baby radio galaxy



#### Tremblay et al. 2011







### Compact Symmetric Objects (CSOs)







### We see AGN :

- from different orientations
- at different evolutionary stages
- in different environments
- with different instruments

Synchrotron Emission depends on the distribution of both relativistic particles and magnetic fields.





# **Faraday** Rotation 58 Plasma Polarized Source $n_e = n_i$ 3 B<sub>II</sub>, $\Psi = \Psi_{\rm o} + RM \,\lambda^2$ $RM = 812 \int_{0}^{L} n_e B_{||} dl radians/m^2$ The University of New Mexic





#### Carilli & Tavlor 2002 (ARA&A









### Frontiers of Plasma Physics: VLA imaging of cluster radio emission on scales 0.1 kpc to 1 Mpc

- I 8 GHz VLA
- rms~2.5uJy
- Frac. Pol. up to 70%
- RM ~ 100 rad m<sup>-2</sup>
- Laboratory for plasma physics on largest scales: Halos, jets, lobes, relics, Xray gas...





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WSRT at 90cm

Feretti et al. 1998

 $B\sim 0.4~\mu G$ 

DECLINATION (B1950)

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#### Pignataro 2025

LOFAR at 60 MHz rms ~ 3 mJy/beam

Dec (J2000)





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III

http://www.nrao.edu/whatisra/mechanisms.shtml http://www.nrao.edu/whatisra/ http://www2.jpl.nasa.gov/radioastronomy/ www.nrao.edu

Synthesis Imaging in Radio Astronomy ASP Vol 180, eds Taylor, Carilli & Perley

This lecture is on the course web page:

http://leo.phys.unm.edu/~gbtaylor/astr423/lectures



