Radio Science & Future Interferometers

T. Beasley
CARMA/Caltech
Owens Valley Radio Observatory

Astronomy

- Gather information about universe from
  - Electromagnetic radiation
  - Particles
  - Gravitational radiation...
- 2-3D imaging – sensitivity, resolution, fidelity
- More Resolution → Interferometry

Electromagnetic spectrum

- Physical properties – temperature, pressure, structure, magnetic fields + physical process → different emissions
- Atoms & molecules → unique radio frequencies

Main Processes - Radio Emission

- Synchrotron radiation - continuum
  - Energetic charged particles accelerating along magnetic field lines
- Thermal emission - continuum
  - Hot → Cool bodies
  - Charged particles interacting in a plasma at T
- Spectral Line emission – spectral line
  - Discrete transitions in atoms and molecules

Synchrotron Radiation

- Polarization properties of radiation provides information on magnetic field geometry
**Jupiter - ATCA – 13cm**

**Supernova Remnants - Crab Nebula**
- Remnant of a supernova 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

**Center of our Galaxy**

**Extragalactic Supernovae**

**SN 1993J in M81**
Bartel, Eckes, Horrobin, Rupen et al.

**Magnetic Field Orientation in Galaxies**

**Radio Jets**
- Cosmic jets are ubiquitous
- They range from extragalactic jets to microquasars in our galaxy
- Central black hole masses range from 1 to billions of solar masses
- Found in ~10% of quasars or other active galactic nuclei
Radio Jets - Theory

- 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

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

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**Spectral Line emission**

- Molecular rotational and vibrational modes - many in mm/submm

- 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), Phenol (phenol acid)

- SL: Doppler shifts + line profiles indicate kinematics and/or physical of sources

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**Neutral Hydrogen in Galaxies**

- B/W-optical image of NGC 6544 from Digital Sky Survey
- Blue-Weberbok 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

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**21 cm Spectral Line Observations**

- VLA 12-pointing mosaic Yusef et al. 1994

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**Molecular Lines - Schöier et al. 2001**

- Rest Frequency (MHz)
- Observations from different sources
Astronomy

- Information via
  - Electromagnetic radiation
  - Particles

- Approach: 2D imaging. Parameters of interest → sensitivity, resolution, fidelity, spectroscopy

- More Angular Resolution → Interferometry
**Future Radio Interferometers**

- **Underway-funded**
  - EVLA (cm/mm)
  - ATA (cm)
  - SZA (cm/mm)
  - CARMA/SZA (mm)
  - ALMA (mm/submm)

- **Proposed**
  - LWA/LOFAR (m)
  - FASR (m/cm)
  - SKA (m/cm)

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**Expanded VLA - EVLA**

- VLA – 27 x 25m reflectors, Y array arms up to 22 km long
- Built in 1970s, dedicated 1980
- Limited upgrading since original construction

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**EVLA Goals**

- Use modern technology to obtain an order of magnitude improvement in most VLA observational capabilities
  - Continuous frequency coverage 1-50 GHz
  - 8 receiver bands, new LO system
  - Up to 1.6 GHz bandwidth per antenna
  - New IF system (8 x 2GHz), fiber optic digital transmission
  - New wideband, high spectral resolution correlator
  - New monitor/control and data processing systems
- Maintain VLA science during the decade-long upgrade

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**EVLA Performance**

<table>
<thead>
<tr>
<th></th>
<th>VLA</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point source sensitivity</td>
<td>10 mJy</td>
<td>0.8 mJy</td>
<td>0.6 mJy</td>
</tr>
<tr>
<td>No. baseline pairs</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Maximum bandwidth per point</td>
<td>0.1 GHz</td>
<td>8 GHz</td>
<td>8 GHz</td>
</tr>
<tr>
<td>No. frequency channels, full BW</td>
<td>16</td>
<td>1,6384</td>
<td>1,6384</td>
</tr>
<tr>
<td>Max. frequency channels</td>
<td>51.2</td>
<td>1,6384 [2,021,444]</td>
<td>1,6384 [2,021,444]</td>
</tr>
<tr>
<td>Max. frequency resolution</td>
<td>381 Hz</td>
<td>~1 Hz</td>
<td>~1 Hz</td>
</tr>
<tr>
<td>(long) Frequency coverage</td>
<td>0.3-55 GHz</td>
<td>25%</td>
<td>75%</td>
</tr>
<tr>
<td>No. baselines</td>
<td>351</td>
<td>351</td>
<td>666</td>
</tr>
<tr>
<td>Spatial resolution @ 5 GHz</td>
<td>0.4&quot;</td>
<td>0.4&quot;</td>
<td>0.04&quot;</td>
</tr>
</tbody>
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**Phase II - New Mexico Array**
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.
- Will speed SETI targeted searching by 100x
  - Will target from 100,000 to million nearby stars
  - Will scan 100 million radio channels
- Start-up scheduled for 2006 – Funded by Paul Allen (Microsoft)

Offset Gregorian Antenna

- 6.1 x 7.0 m Primary
- Log-periodic Feed
- 2.4 m Secondary
- Az-Ell Drive
- Shroud
  (feed can’t see ground or array)

ATA Science

- SETI
  - 100,000 FGK stars
  - Galactic plane survey (2nd generation DSP)
- HI
  - All sky HI, z < 0.03, Milky Way at 100 s
  - Large area to z ~ 0.1 or more
  - Zeeman measurements – magnetic field
- Temporal Variables
  - Pulsar Timing Array
  - Pulsar survey follow-ups
  - Extreme Scattering Events
  - Transients (e.g. gamma ray bursts)

Caltech
Six 10.4 m dishes

CARMA

Berkeley – Illinois – Maryland
Nine 6.1 m dishes

Chicago
Eight 3.5 m dishes
key features
- Heterogeneous array (890 m²) at new 2200m site
- six 10.4m antennas - OVRO
- nine 6.1m antennas - BIMA
- eight 3.5m antennas - SZA
- Frequency: 22-30GHz, 70-118 GHz, 220-270 GHz
- Arrays: four configs: 100m – 2000m + SZA
- Imaging over wide range of angular scales:
  CARMA: 0.15-30”, SZA: 30-180”
- More antennas ⇒ High-fidelity imaging + snapshot
- Mosaicing (point-click + OTF)

Millimeter science
- Studies of circumstellar/protoplanetary disks, stellar outflows, stellar winds from evolved stars
- Examine SF environments of nearby & distant galaxies
- Explore Solar System: Sun, planets, comets, KBOs
- Probe astrochemistry of ISM, IPM
- Image distant universe: CO/SF in high-redshift galaxies
- Cosmology experiments – SZ, CMB polarization

Atacama Large Millimeter Array

Most Compact configuration. Baseline extendible up to 14 km

ALMA

<table>
<thead>
<tr>
<th>Antennas</th>
<th>64 x 12 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collecting area</td>
<td>&gt;7000 m²</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.02 λ mm</td>
</tr>
<tr>
<td>Receivers</td>
<td>10 bands: 0.3 – 7 mm (36 - 850 GHz)</td>
</tr>
<tr>
<td>Correlator</td>
<td>2016 baselines</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>16 GHz/baseline</td>
</tr>
<tr>
<td>Spectral channels</td>
<td>4096 per IF (8 x 2 GHz)</td>
</tr>
</tbody>
</table>
ALMA Science

- Formation of galaxies and clusters
- Formation of stars
- Formation of planets
- Creation of the elements
  - Old stellar atmospheres
  - Supernova ejecta
- Low temperature thermal science
- Planetary composition and weather
- Structure of Interstellar gas and dust
- Astrochemistry and the origins of life
**Low Frequency Science Targets**

- Redshifted HI from the Epoch of Reionization
- High-z standards
- Galaxy clusters and the ICM
- Cosmic-ray distribution, and air-shower radio bursts
- Steep spectrum and foreshock galaxies
- Supernova remnants and ISM energy budget
- Interstellar recombination lines
- Nearby pulsars, ghost nebulae
- Extragalactic gas giant planetary radio emission
- Stellar flares
- Interstellar medium propagation effects
- Transients, GRB and AGN
- Event Correlation, bunching
- Solar radio studies
- OME detection, mapping by IPS, scattering
- Extreme high-altitude ionosphere tomography
- Passive ionospheric radar

**Frequency Agile Solar Radiotelescope (FASR)**

- Of order 100 antennas (5000 baselines)
- Better than 1" imaging at 1s time resolution
- Full frequency coverage 0.1-30 GHz
- Designed Specifically for Solar Imaging
  - Full Sun (at least 12 GHz)
  - Designed for solar spatial scales
  - Designed for solar brightness variability

**Square Kilometer Array - SKA**

Next generation "discovery" telescope in the meter to centimeter wavelength region with

- 100 x sensitivity of EVLA
- Large instantaneous field of view
- New modes of operation (multiple simultaneous users - multibeaming)

→ extremely powerful survey telescope with the capability to follow up individual objects with high angular and time resolution

**SKA Design Goals**

- Sensitivity: $S_{\text{vis}} = 2 \times 10^{-2} \text{ m}^2 / \text{K}$
- Surface brightness sensitivity: 1K at 0.1 arcsec (continuum)
- Frequency range: 0.15 – 22 GHz
- Redshift coverage: $z<0.5$ (HI); $z<4.2$ (CO (1→0))
- Imaging field of view: 1 deg at 1.4 GHz
- Multi-beam capability: $N_{\text{beam}} = 120$
- Angular resolution: $\leq 0.015$ arcsec at 1.4 GHz
- Number of spatial pixels: $>10^6$
- Instantaneous bandwidth: 0.5 + frequency/5 GHz
- Number of spectral channels: $>10^4$
- Image dynamic range: 10$^6$
- Polarisation purity: 40 dB

**SKA scientific drivers**

- Dark Ages and Epoch of Reionization
  - Ionization of neutral IGM
  - Properties of first luminous objects
- Large Scale Structure in the Universe
  - Dark energy as function of redshift
- Evolution of galaxies
  - Growth of black holes
  - Star formation rate
  - Protostellar disks
- Probing Gravity through pulsars
  - Black hole binaries as probes of strong gravity
  - Low-frequency gravity wave background
- Origin and evolution of Cosmic Magnetic Fields
  - Large scales, primordial fields
  - Small scales, turbulence & dynamos
1 deg² (minimum) field-of-view for surveys and transient events

Dark energy
- Alters distance measures in cosmology incl. evolution of Hubble parameter with time and growth of structure
- Power spectrum of the clustering of galaxies (angular/redshift) likely to contain a signature of acoustic oscillations at time of recombination
- Use scale of acoustic oscillations as a cosmological standard ruler to measure equation of state of dark energy at intermediate redshift and possibly its evolution. 1<z<2 optimal.
- SKA: In 360 hours and a 4 deg² FOV (@1.4) SKA will detect ~2x10⁸ HI galaxies. It can then cover ‘whole’ sky in ~5 years with 8 simultaneous FOVs.

Achieving the SKA
- Reduce overall cost per m² of collecting area by a factor ~10 cf. current arrays
- Maximising flexibility of design while...
- Minimising maintenance/running costs
  Take advantage of massive industrial R&D in fibre optics and electronics industries (“Moore’s Law” to ~2015) for transport and handling of data
  Develop innovative, cost effective, new concepts for collectors

History of IGM
Epoch of Reionization (EoR)
- Bench-mark in cosmic structure formation indicating the first luminous structures
- Search for HI spectral signature...... tough....

N x Arecibo
Kara region for array of large Arecibo-like Telescopes
D > 200 m
• 150-200m diameter stations
• large F/D
• focal platform supported by aerostat
• almost flat panels
• 150 MHz to 22 GHz
• DRAO, U Calgary

Large Adaptive Reflector

Cylindrical reflector
• 111x15 m elements
• 600 elements
• 100 MHz - >9 GHz
• multifielding possible

Luneberg lenses
• 7 m spheres
• in patches 180 m in diameter
• 300 patches
• CSIRO/ATNF

Large N small D:
the Allen Telescope Array
• SETI Institute
• UC Berkeley
• 100m equivalent
• 350 x 6.1 m parabolas
• 0.5-11 GHz (simultaneously)
• 2.3° FOV at 1.4 GHz
• 4 simultaneous beams
• 206 antennas in 2005

Phased array concept
Basic idea: replace mechanical pointing & beam forming by electronic means
SKA

- Initial site analyses submitted by Australia, China, South Africa, and USA in May 2003
- Initial site analysis by Brazil in preparation
- RFI and tropospheric stability testing at candidate sites in 2004-5
- Technology decision – 2007/2008
- Construction – 2012+

Summary

- Future: Radio astronomy ↔ Interferometry
- Current arrays going strong, new arrays under development (mm)
- Importance of any field can grow rapidly, multiple routes to knowledge valuable...
- Challenges – cheap collecting area, data transport & processing, public outreach, international collaboration (mho)
- Understanding of techniques, limitations, possibilities important – summer school

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