Course II:
Compact Objects, the Dynamic Radio Sky, and 21st Century Radio Telescope Facilities

Jim Cordes
Cornell University

Five Lectures:
1. Astrophysics of neutron stars and other compact objects
2. Plasma propagation effects (ISM, IGM, ionosphere)
3. Astrometry of compact objects
4. The dynamic radio sky (transients and variability)
5. New radio telescope arrays for key science and discovery

Cornell University

Course II Lecture 5
New Radio Telescope Arrays for Key Science and Discovery

- SKA Science and Implementation
- Technology development
- Precursor arrays
- Pathfinding (science, technology)
- Timeline

The Square Kilometer Array

- The SKA Project
  - Early 90s: the "Hydrogen" telescope
  - Now rich diverse science case
  - International project
- SKA science case
  - 1990s Taylor & Braun
  - 2003-2004 SWG of International SKA Project
  - Fundamental questions in physics, astrophysics and astrobiology + Discovery
- Specifications and Technology: Aspirations:
  - Array with ×20-50 increase in sensitivity over existing telescopes (~ 0.5 km^2/30 K)
  - Frequency range: 0.1 – 25 GHz (nominal) (0.06 – 35 GHz)
- Innovative designs needed for performance and cost
- Implementation
  - Siting: two acceptable sites (SA, WA): decision in 2012
  - Technology development/Pathfinders/Precursors
  - Timeline: Phased deployment 2016→ 2030
  - SKA as a Radio Synoptic Survey Telescope (RSST)

Science/technical memo series:
http://www.skatelescope.org

Reference Material

http://skatelescope.org/publications

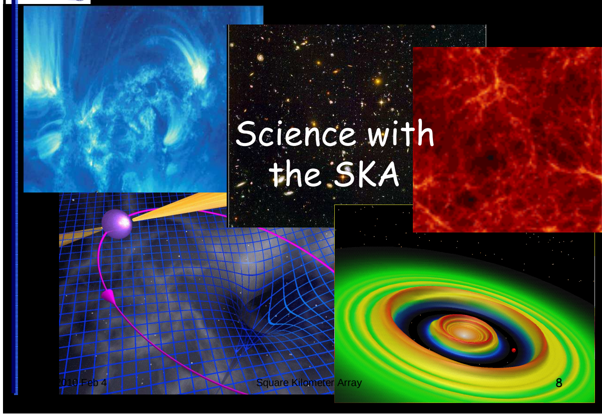
- *Preliminary Specifications for the Square Kilometer Array* (SKA Memo 100, 2007) (Includes science specs)
- *Concept Design for SKA Phase 1*
- (Memo 125, 2010)
- *Sensitive Continuum Surveys with the SKA: Goals and Challenges* (Memo 114, 2009)
- *Pulsar Searches and Timing with the SKA*
- (Memo 105, 2008)
- *SKA Exascale Software Challenges*
- (Memo 128,2010)
- *Low Power Correlator Architecture for the Mid-frequency SKA*
- (Memo 133, 2011)
- *The Giant Systolic Array: Straw-man Proposal for a Multi-mega Baseline Correlator for the SKA*
- (Memo 126, 2010)
- *Cloud computing and the SKA*
- (Memo 134, 2011)

SKA Movie

Antennas Animation

Science Goals and Frontiers

- Science areas:
  - Fundamental physics (gravity, dark-matter particles, dark energy, origin of cosmic rays)
  - Cosmology, galaxy/stellar evolution and formation, including massive black holes
  - Cradles of life
    - protoplanetary disks, organic molecules, exoplanets, SETI
- The quest for unknown unknowns is alive and well (c.f. Harwit)
  - radio λλ have a great track record for discovery (quasars, CMB, pulsars)
  - the time domain



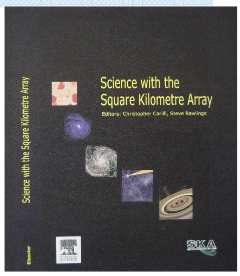
SKA Science

- International Science Working Group (~30 members)
- Full science case published in *New Astronomy Reviews*, Vol 48, 2004

- Five Key Science Projects:

1. Probing the Dark Ages
2. Galaxy Evolution, Cosmology and Dark Energy
3. The Origin & Evolution of Cosmic Magnetism
4. Strong Field Tests of Gravity Using Pulsars and Black Holes
5. The Cradle of Life

… plus **The Exploration of the Unknown** as an underlying philosophy for design & costing



http://www.skatelescope.org

Pathfinders and Precursors for the SKA

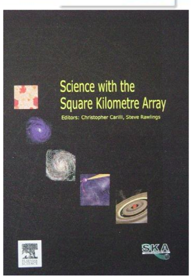
Jim Cordes (Cornell)

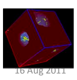
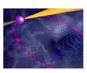
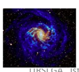
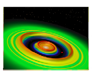
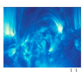
- Science pathfinding + technology pathfinding
  - dual motivations
  - Near-term science returns from long-term investment (e.g. SKA feeds/receivers on existing telescopes)
- Sensor development
- Operations
  - surveys, data throughput, RFI mitigation
- Cyber-infrastructure

SKA Key Science

International working group
- Strong-field Tests of Gravity with Pulsars and Black Holes
- Galaxy Evolution, Cosmology, & Dark Energy
- Emerging from the Dark Ages and the Epoch of Reionization
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

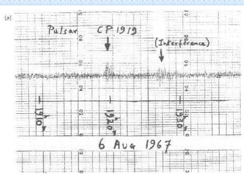
With design philosophy of *Exploration of the Unknown*

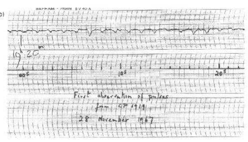


Exploration of the Unknown

Unplanned discoveries
- Pulsars
- Microwave Background
- Cosmic Evolution
- Dark Matter in galaxies
- Quasars
- Jets + Superluminal motion





SKA Discovery Potential
10^4 x existing radio telescopes

Science Goals: Present & Future

Broad Science Areas

- Astrobiology
- Astrophysics
- Cosmology
- Fundamental Physics
- *Discovery*
  - time domain, astrometry + …

←→

Observational Axes

- Frequency (range, res'n)
- Time (ns → yr)
- Sensitivity (A/T)
- Polarization purity
- Deep imaging
- High-resolution imaging (including astrometry)

Data Management

Representative Science Drivers

- *Evolution of cosmic hydrogen:*
  - *Epoch of Reionization*: many talks already (clear that R&D needed for telescope design, analysis, processing, RFI mitigation)
  - *Galaxy evolution:* from the EoR to the present (z < 6.5 or so)
    - large scale surveys (wide fields, wide bands, long integrations)
- *Deep imaging surveys:*
  - Source populations below a few μJy
  - Supermassive black hole evolution with z
  - Magnetic universe (Faraday rotation, polarized synchrotron, pulsars)
  - Cross-wavelength studies and finding surveys
  - New source classes?
- *Gravity: Pulsar surveys and timing:*
  - Galactic census of pulsars (few × 10^4 beamed toward us)
  - Relativistic binaries down to ~ 15 minute orbits
  - Millisecond pulsars clocks for nHz gravitational wave detection
- *Transients:*
  - Large phase space (frequency, time scale, flux density)
  - Flexibility needed, large data volumes, real time analysis + archival capability

Related Astro2010 Science Whitepapers

http://www7.nationalacademies.org/bpa/Astro2010_SWP_byTitle.html

Fundamental Physics (Gravity) and Early Universe:

- Tests of Gravity and NS Properties from Precision Pulsar Timing and Interferometry (Cordes et al.)
- Gravitational Wave Astronomy Using Pulsars: Massive Black Hole Mergers & the Early Universe (Demorest et al.)
- The Galactic Center: A Laboratory for Fundamental Astrophysics and Galactic Nuclei (Ghez et al.)

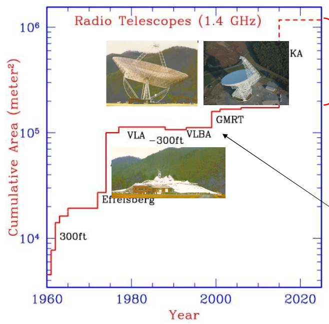
NS Astrophysics:

- Constraining the Bulk Properties of Dense Matter by Measuring Millisecond Pulsar Masses (Freire et al.)
- Extreme Astrophysics with NS (Lai et al.)
- X-ray Timing of NS: Astrophysical Probes of Extreme Physics (Arzoumanian et al.)
- The Behavior of Matter Under Extreme Conditions (Paerels et al.)
- Probing NS with Gravitational Waves (Owen et al.)

Transients and Exploration:

- The Dynamic Sky: An Opportunity for Discovery (Lazio et al.)
- The Exploration of the Unknown (Kellermann et al.)

The Collecting Area Plateau in Radio Astronomy

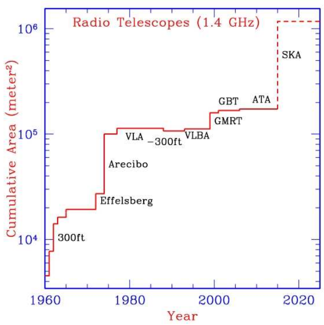


Increased collecting area enables:

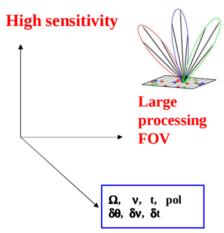
- **Detection of L* galaxies in HI at z ~2**
- **Epoch of Reionization analysis**
- **GRB afterglows ×100 fainter than currently**
- **Detection/timing of pulsars near Sgr A***
- **Gap structure in young, protoplanetary disks**

Growth in sensitivity over the last three decades has exploited low-noise devices, developments in digital signal processing bandwidth, and calibration and imaging techniques.

Combine Greater Sensitivity with Wide Field of View Processing

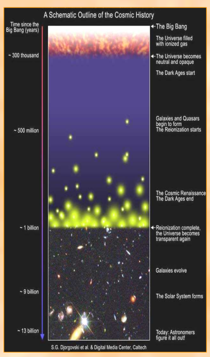


The SKA combines a > ×20 boost in sensitivity with unprecedented utilization of the field of view



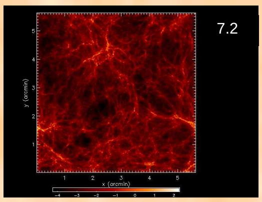
Probing the Dark Ages

COSMIC HISTORY OF THE UNIVERSE



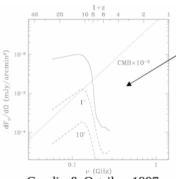
Challenges

- **Widefield imaging at low frequencies (ionosphere)**
- **Galactic foregrounds (polarized synchrotron)**
- **Point source removal**
- **Radio Frequency Interference**

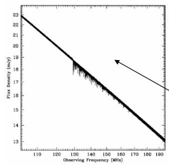


Probing Reionization with the 21 cm Line

$6 \le z \le 23 \Rightarrow 200$ MHz $\ge \nu \ge 60$ MHz



Gnedin & Ostriker 1997

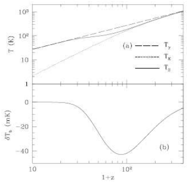


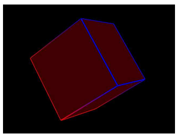
Carilli, Gnedin & Owen 2002

- Global reionization signature in radio spectrum
- Minihalos, protogalaxies and AGN HII regions
- Tomography: $\delta T_b(\boldsymbol{\theta},\nu)$
- Non-Gaussian fluctuations (bispectrum)
- Cosmic D/H ratio using H fluctuations as template for D
- Absorption against the first AGNs (21-cm forest)

$$\tau = 0.01 \left(\frac{T_{\rm CMB}}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2} x_{\rm HI}(1+\delta)$$

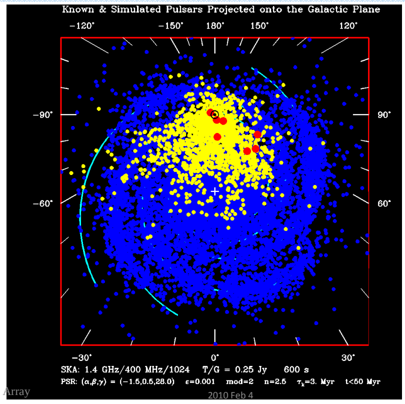
Furlanetto et al. 2006





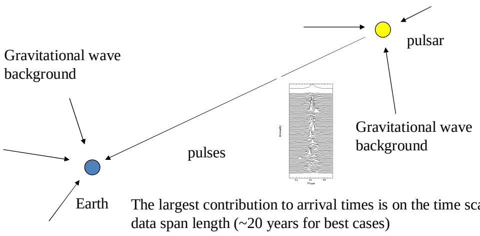
N. Gnedin

A Galactic Census of Pulsars



2000 known … about 20k to go!

Pulsars as Gravitational Wave Detectors

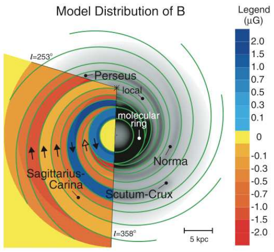


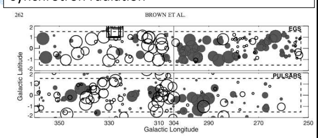
The largest contribution to arrival times is on the time scale of the total data span length (~20 years for best cases)

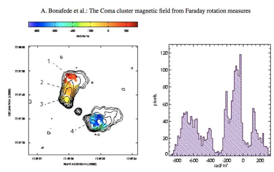
$$\Omega_g = \frac{\rho_g}{\rho_c} \propto \frac{(\text{rms timing residual})^2}{(\text{data set length})^4}$$

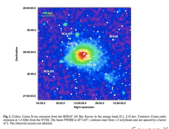
Cosmic Magnetism

Faraday rotation measure, Zeeman splitting, synchrotron radiation

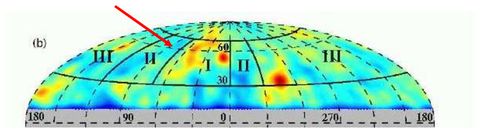




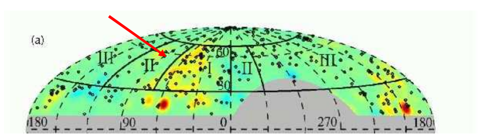




Faraday Signature of ICM & IGM



2MASS galaxy column density



Smoothed RMs from extragalactic sources

Xu et al. (2005)

- B ~ 0.3 μG on scales ~ 0.5 Mpc in Hercules supercluster?

Astronomical Requirements

- High Redshift Coverage ⇔ Wavelength/Frequency Coverage
  - Hydrogen λ21 cm, 1.4 GHz
    - Epoch of Reionization: z~13 to z~6 or 100 to 200 MHz
  - Carbon monoxide λ3 mm, 115 GHz + other transitions
    - First galaxies: z ~ 10? or 12 GHz and higher
  - Water λ1.3cm, 22 GHz
    - Precision determination of Hubble constant to z~1
  - Other molecules:
  - Continuum observations: all wavelengths
- Radio astronomy requires observations outside narrow, protected bands defined long ago
  - More reason to go to remote sites (including the Moon)

Astronomical Requirements

- Much higher point-source sensitivity than current
  - collecting area $A_{effective}$
  - system temperature T_{system}
  - bandwidth B

$$\Delta S^{-1} \propto \sqrt{2BT}\left(\frac{A_{\rm effective}}{T_{\rm system}}\right)$$

- Much higher survey speed

$$SS = \frac{dV}{dt} = \frac{\text{volume surveyed}}{\text{time}}$$

$$\propto \Omega_{\rm FoV} B \left(\frac{A_{\rm effective}}{T_{\rm system}}\right)^2$$

- High-dynamic range imaging: 10^7:1
  - source confusion in continuum (sub-μJy)

Implementation of the SKA

Three frequency bands:

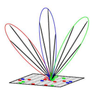
Band	Nominal Band Frequencies	
Low	100 to 300 MHz	Epoch of Reionization, transients
Mid	0.3 to 10 GHz	High-z galaxies (hydrogen), SF galaxies and AGNs, cosmic magnetism, pulsars, transients, SETI
High	10 to 25 GHz +	High-z CO, protoplanetary disks, Galactic center pulsars, SETI

Technologies:

Low frequencies	dipole arrays	"sparse" dipole arrays
Mid frequencies	aperture arrays	"dense" arrays
	dishes + single pixel feeds	
	dishes + phased-array feeds	"dense" arrays
High frequencies	dishes + single pixel feeds, feed clusters	radio cameras

Implementations

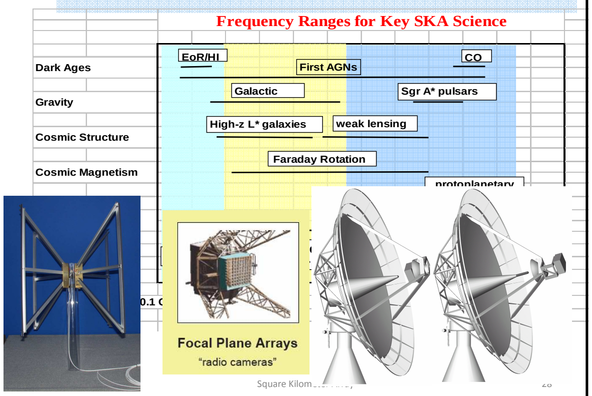
$A_{effective}$: Large-N arrays* (dipoles, dishes)
T_{system}: Low-noise devices
Quiet sites: Radio quiet zones + RFI mitigation
Frequency coverage and Field of View (FoV):
Broadband feeds (10:1)
Phased-array feeds
Radio cameras, multiple-pixel feeds



Digital: High bw networking, DSP, processing
"climbing mount exaflop"

➔ All systems optimized for large-volume production

SKA Frequencies and Technologies



Broad SKA Timeline

- up to present: science definition, R&D, technology development
  - PrepSKA, US TDP
  - Project office (SPDO) at University of Manchester (UK)
- 2012-2015: "pre-construction phase"
  - New governance (fewer countries)
  - New project office and director
- 2016: begin construction on Phase 1
- 2020: Phase 1 operations
- 2020- … : Phase 2 construction, ops

Major Science Goals of SKA Phase 1

I. **Understanding the history and role of neutral Hydrogen in the Universe from the dark ages to the present-day, and**

II. **Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity (including General Relativity and quantum gravity), to discover gravitational waves from cosmological sources, and to determine the equation of state of nuclear matter.**

Comments:

- Addressing the themes of "Origins" and "Fundamental Physics", these two major goals are supplemented with the theme of "Discovery".
- A wide variety of different studies will be enabled *e.g.* detecting and imaging radio continuum emission from galaxies and active galactic nuclei to trace the evolution of galaxies, black holes, star formation and magnetism from the dawn of galaxies to the present era. Large HI galaxy surveys for cosmology and dark energy may also be conducted, in addition to transient searches (including SETI).

Technical Concept for SKA_1

1) **Low-frequency sparse aperture array** with an A/T_{sys} of up to 2000 m²/K operating at frequencies between 70 and 450 MHz. The array will be centrally condensed but some of the collecting area will be in stations located out to a maximum baseline length of 100 km from the core, and

2) **Dish array with A_{eff}/T_{sys} of up to 1000 m²/K** using approximately two hundred and fifty 15-metre antennas, employing an instrumentation package that will use single-pixel feeds to provide high sensitivity and excellent polarisation characteristics over a frequency range of 0.45-3 GHz. The array will be centrally condensed but some of the elements will be co-located with the sparse aperture array stations out to a maximum baseline length of 100 km from the core.

The dish design will be SKA_2 compliant in terms of its overall performance specification, including a target rms. surface accuracy of 0.5 mm or better.

What is a Precursor/Pathfinder?

- ***Precursor***:
  - a telescope on either of the two acceptable SKA core sites
    - Western Australia (Murchison)
      - ASKAP: mid-frequency dish array (broad science)
        - » wide-field survey instrument (phased-array feed)
      - MWA: low-f array (EoR +)
    - South Africa (Karoo)
      - MeerKAT: mid-frequency dish array (broad science)
        - » single-pixel feeds for higher A/T science
      - PAPER: EoR
    - All are science instruments in their own right
- ***Pathfinder***:
  - telescopes/activities that develop elements necessary for the SKA (a long list!)

Science Pathfinding

- Every project wants to be an SKA pathfinder!
- Key science areas:
  1. **Epoch of Reionization**: Need a detection of the EoR signal in the 100-200 MHz band
     - LOFAR = Low frequency Array (Europe)
     - PAPER = Precision Array to Probe the Epoch of Reionization (UCB, NRAO, South Africa)
     - MWA = Murchison Widefield Array (MIT, CfA/SAO, Australia)
  2. **Galaxies, Pulsars & Gravity, Magnetism**
     Arecibo ALFA Surveys (ALFALFA, PALFA, GALFACTS)
  3. **High frequency science** (protoplanetary disks, organic molecules, pulsars in the Galactic Center)
     - EVLA, ALMA over the next decade

SKA Pathfinding

- SKA is ultimate goal, though long-term program
- Precursors and many pathfinders in existence or under construction

> Data challenges before SKA comes on-line

> Scalability could be an issue

Front End Technology Development

- Elements of SKA development:
  - Reflectors (symmetric, offset Gregorian)
  - Wideband single-pixel feeds
  - Phased-array feeds (PAFs)
  - Phased Arrays (sparse, dense)
  - LNAs + digitizers (low cost cryo)
  - Verification programs within current and preconstruction phases for SKA (DVP, AAVP)
- Precursors and some pathfinders: ditto on technical elements

ASKAP (Australian SKA Pathfinder (Precursor)

Key technologies:

Three axis, symmetric antenna (beam correction, processing)

Phased-Array Feed (survey speed)

Aggressive cyber-i dev

The specification for ASKAP is:

- A total collecting area of approximately 4,000 square metres, from 36 antennas each 12 metres in diameter
- System temperature less than 50 K
- Frequency range from 700 MHz to 1.8 GHz
- 300 MHz instantaneous bandwidth
- At least 30 independent beams, each of about 1 square degree, yielding a 30 square degree field-of-view at 1.4 GHz
- Maximum baseline of approximately 6 km
- Full cross-correlation of all antennas
- Possible remote array station capability located in NSW, approximately 3,000 km from the core site.

First observations (full array): 2013

http://www.atnf.csiro.au/projects/askap/

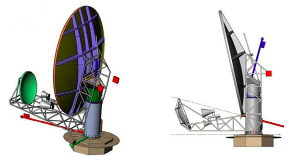
ASKAP Science (Key Projects)

A zoo of acronyms: **Molecules, Pulsars, Fundamental Physics, Deep continuum surveys, Magnetism, Deep HI surveys, Transients**

The ten ASKAP Survey Science Projects are:

- Evolutionary Map of the Universe (EMU)
- Widefield ASKAP L-Band Legacy All-Sky Blind Survey (WALLABY)
- The First Large Absorption Survey in HI (FLASH)
- An ASKAP Survey for Variables and Slow Transients (VAST)
- The Galactic ASKAP Spectral Line Survey (GASKAP)
- Polarization Sky Survey of the Universe's Magnetism (POSSUM)
- The Commensal Real-time ASKAP Fast Transients survey (CRAFT)
- Deep Investigations of Neutral Gas Origins (DINGO)
- The High Resolution Components of ASKAP: Meeting the Long Baseline Specifications for the SKA (VLBI)
- Compact Objects with ASKAP: Surveys and Timing (COAST).

MeerKAT



Key technologies:

Clear aperture (OG optics)

Octave feeds

Attention to high-DR imaging

MeerKAT: Specifications for array, antennae and receivers

Number of antennas: 64
Dish diameter: 13.5 m
Minimum baseline: 29 m
Maximum baseline: 20 km
Frequency bands (receivers): 0.58 - 1.015 GHz; 1 - 1.75 GHz; 8 - 14.5 GHz
Continuum imaging dynamic range at 1.4 GHz: 60 dB
Line-to-line dynamic range at 1.4 GHz: 40 dB
Mosaicing imaging dynamic range at 14 GHz: 27 dB
Linear polarisation cross coupling across -3 dB beam: -30 dB

First observations with full array: 2016

http://www.ska.ac.za/meerkat/

MeerKAT Science

A zoo of science acronyms!

Molecules (Dark Ages)
Pulsars
Fundamental Physics
Deep continuum surveys
Deep HI surveys
Transients

MeerKAT science projects

Testing Einstein's theory of gravity and gravitational radiation - Investigating the physics of enigmatic neutron stars through observations of pulsars.

LADUMA (Looking at the Distant Universe with the MeerKAT Array) - An ultra-deep survey of neutral hydrogen gas in the early universe.

MESMER (MeerKAT Search for Molecules in the Epoch of Re-ionisation) - Searching for CO at high red-shift (z>7) to investigate the role of molecular hydrogen in the early universe.

MeerKAT Absorption Line Survey for atomic hydrogen and OH lines in absorption against distant continuum sources (OH line ratios may give clues about changes in the fundamental constants in the early universe).

MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters) - Investigations of different types of galaxies; dark matter and the cosmic web.

TRAPUM (Transients and Pulsars with MeerKAT) - Searching for, and investigating new and exotic pulsars.

A MeerKAT HI Survey of the Fornax Cluster (Galaxy formation and evolution in the cluster environment).

MeerGAL (MeerKAT High Frequency Galactic Plane Survey) - Galactic structure and dynamics, distribution of ionised gas, recombination lines, interstellar molecular gas and masers.

MIGHTEE (MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey) - Deep continuum observations of the earliest radio galaxies

ThunderKAT (The Hunt for Dynamic and Explosive Radio Transients with MeerKAT) - eg gamma ray bursts, novae and supernovae, plus new types of transient radio sources.

Other: VLBI, SETI, space probe telemetry

SKA Reflector Options

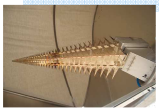
- ASKAP antenna:
  - 12m, symmetric, 3 axis mount to address imaging
  - CETC54 design: metal, heavy, low cost (for now)
- MeerKAT antenna:
  - initially a symmetric, composite design (12m), KAT7
  - now pursuing an offset Gregorian composite design
  - joint development with TDP still possible
  - MeerKAT schedule may not allow deployment of an SKA antenna
- DVA-1: An SKA antenna prototype
  - OG 15m composite
  - Aggressive attention to costs in optics and mechanical design
  - Could have application in SKA precursor(s) or other RA apps

SKA Antenna DVA-1

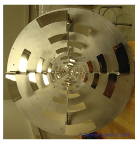
- Joint project of Cornell (PI lead institution), DRAO (Canada), NRAO, SPDO (Manchester)
- Designed for mass production and low mass
- Carbon composite reflector
- Lightweight backup structure
- Offset Gregorian optics (no blockage → low side lobes)
- Accommodates conventional feeds, wideband feeds, and PAFs

15-m Gregorian Offset Design

Broadband Feeds



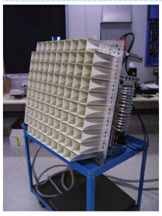
Allen Telescope Array: 11:1 frequency range (1-11 GHz)
Log periodic; Cryo-cooled receiver integrated into tip
(J. Welch, UC Berkeley/SETI Institute)



Quasi-self complementary feed (10:1)
(German Cortes, Cornell University)

Quad-ridge (10:1)
(Lindgren/Caltech)
(Sandy Weinreb)

Phased Array Feeds



Vivaldi structures
(ASTRON)

Figure 4: The 5x4 checkerboard array being assembled.

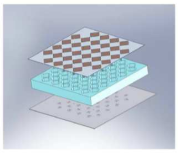


Figure 5: "exploded" view of the 5x4 checkerboard array.

Checkerboard feed
(ATNF)

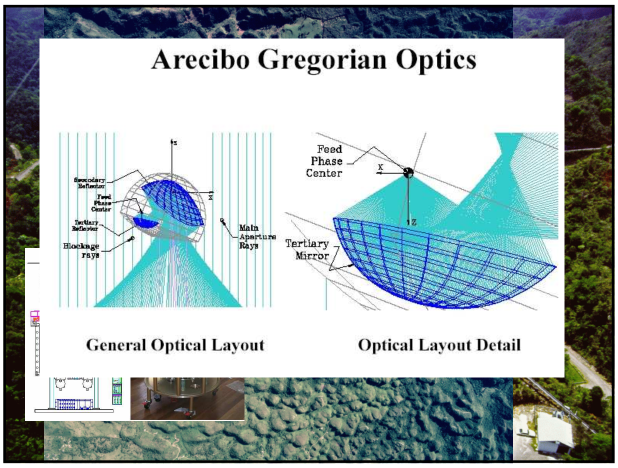
Challenges:
- Digital beam forming with wide bandwidth
- Low system noise with uncooled systems
- Weight and cost

Phased Array Feeds

- PAFs = a path to achieving high survey speed, high efficiency, and wide-field science (transients)
- PAFs relevant to ~ 0.5 – 1.5 GHz (near term)
- PAFSKA = PrepSKA group of PAF developers
  - ASTRON, ATNF/CASS, DRAO, BYU (NRAO?)
- Concerns about PAF performance in OG optics
  - Current status: PAFs + OG workable, but there are design, cost implications (see documents)
  - Ongoing communication between PAFSKA, DVA-1 groups on PAF simulations in OG optics
  - PAFs need to be tested on a prototype SKA antenna!

Phased-Array Feed Development

- PAFSKA = global coordination group
- PAFs being developed for ASKAP, Westerbork (APERTIF), Arecibo and elsewhere
- Provides 20 to 40 separate beams
- Primary issues:
  - System noise
  - Small to moderate total bandwidths, RF < 1.5 GHz
  - Polarization performance
- Large-N dish arrays: PAFs are uncooled
- Arecibo: fully cooled, L band



Arecibo Focal Phase Array

National Astronomy and Ionosphere Center

Cornell University

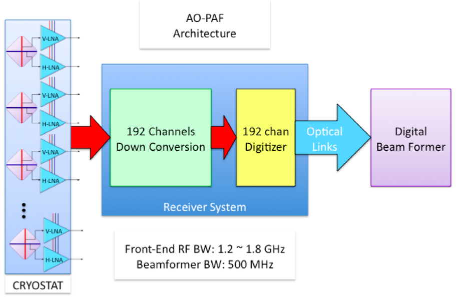
AO-PAF

Front-End		
Number of Elements	91	
Dual Polarization		
Frequency Range	1.2 – 1.8	GHz
System Temperature	30 – 35	K
A/D Digitizer		
A/D Sampling Number of bits	8 - 12	bits
Channel Bandwidth	1	MHz
Digital Beam Former		
Number of simultaneous Beams	40	Min
Bandwidth	500	MHz
Channel width	1	MHz
Arithmetic throughput	12	Bits
Spectrometers		
Resolution (over 100 MHz)	5	KHz

Arecibo Focal Phase Array

National Astronomy and Ionosphere Center

Cornell University

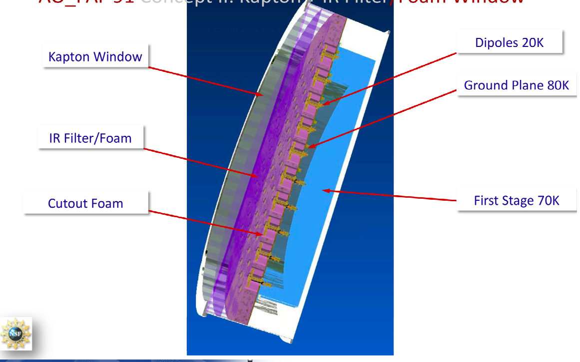


Arecibo Focal Phased Array Architecture
© Germán Cortés 2011

Cryogenics Feasibility Study

AO_PAF 91 Concept II: Kapton + IR Filter/Foam Window

Cornell University



Arecibo Focal Phase Array
Survey Speed Factor

National Astronomy and Ionosphere Center

Cornell University

# of beams — Bandwidth — Beam Solid Angle

$$SVS = N_b \Omega_b BW (A_{eff}/T_{sys})^2$$

L-Band	N_b	Ω_b	BW	A_{eff}	T_{SYS}	A_{EFF}/T_{SYS}	SVS/ AO_{SVS}
		[deg²]	[MHz]	[m²]	[K]	[m²/K]	
AO	1	0.0028	300	32750	27	1213	1
ALFA	7	0.0028	300	32750	27	1213	7
AO FPA	40	0.0028	500	32750	35	936	39.7

Arecibo Focal Phased Array Architecture
© Germán Cortés 2011

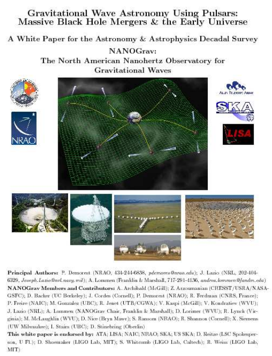
International Pulsar Timing Array (IPTA)

IPTA = EPTA + NANOGrav + PPTA

- Data sharing (global telescopes)
- Joint development of resources (backends, arrays)

Favorable response from Astro2010:

- GW astronomy one of 5 key discovery areas.
- PTAs highly recommended by RMS panel.

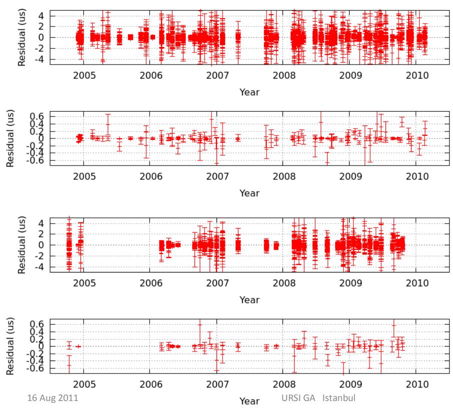


IPTA Goals

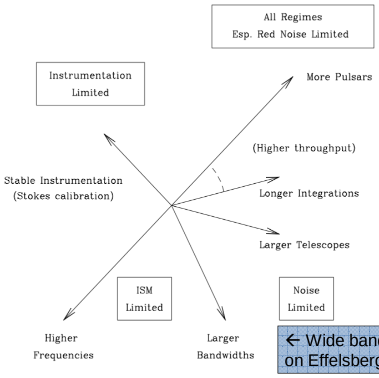
- Detect GWs from cosmological sources
  - GW background(s)
    - SMBH inspirals, cosmic strings
    - Single sources (nearby SMBH binaries, bursts)
  - Arecibo, GBT, Effelsberg, Jodrell, Nancay, WSRT, Sardinia, Parkes (also LEAP = coherent sum of European antennas)
  - Later: MeerKAT
- Numerous challenges exist that must be addressed to allow detection
- The first detection could be soon but may require SKA Phase 1
- SKA Phase 2 is certainly needed to fulfill the potential of GW astrophysics

Best timing residuals versus time:

(Demorest et al. 2011)



Improving Timing Precision and GW Sensitivity



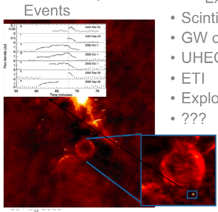
Depending on noise regime, better sensitivity comes from different improvements.

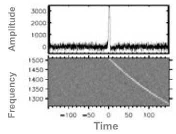
Increasing the number of *quality* MSPs is guaranteed to increase sensitivity to GWs

← Wide band SKA feeds deployed on Effelsberg, Arecibo, GBT

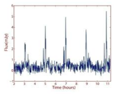
The Dynamic Radio Sky

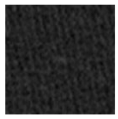
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?
- Microquasars
- Tidal Disruption Events
- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Scintillation
- GW counterparts
- UHECRs
- ETI
- Exploding black holes
- ???





Rotating Radio Transients (RRATS)

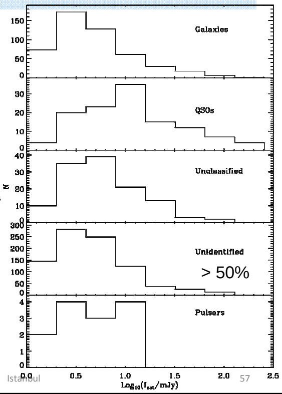


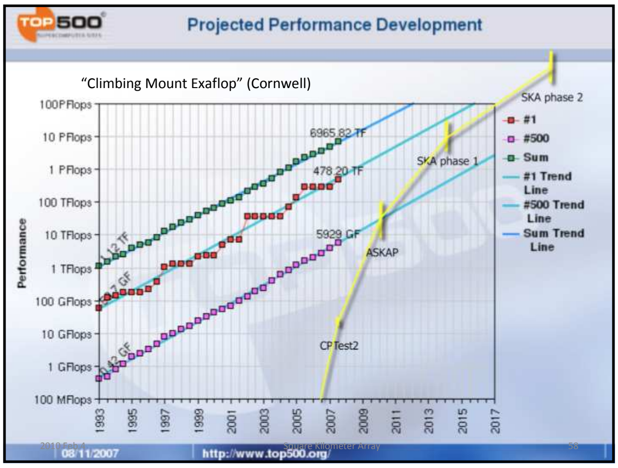


Pulsating Brown Dwarfs

Cross-λ Transient Studies

- Massive surveys across EM spectrum
- All survey telescopes relevant!
- Cross IDs (OIR→ radio, etc.) for source classification and ID of new source classes
- Example: VLA/FIRST survey (L-band) transients/variables
  - Thyagarajan et al. 2011





Cyber-infrastructure

- What is this?
- "Big Data" theme of SKA 2011 (Banff)
- Astronomy definition (suggested):

The mix of post-array processing + storage + networking + databases + user interfaces needed to accomplish science goals + long-term curation (100+ yr) of relevant data products

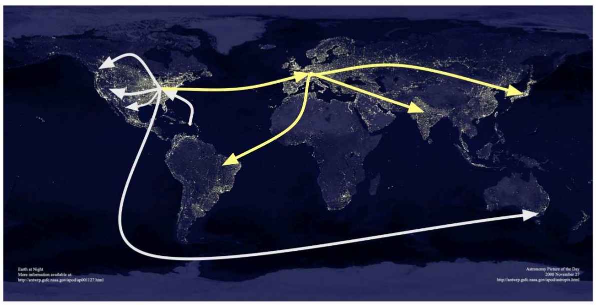
- Stakeholders are globally distributed
- Regional communities
- Needs to support R&D (algorithm development) as well as niche science processing
- There is no correct scheme!

Exaflops, Exabytes (Exascale)

, Petabytes/s

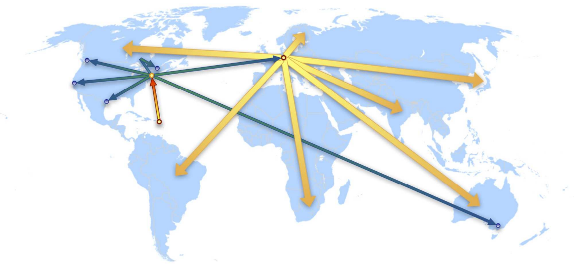
Arecibo Pulsar Survey Data Flow

Purpose 1: Survey analysis at multiple sites



Arecibo Pulsar Survey Data Flow

Purpose 2: Einstein@Home citizen science: extended survey analysis: 200,000 volunteers ➔ petaflops + megawatts (2 discoveries so far)



Why CyberSKA?

- PALFA is an international consortium.
  - Two-dozen members from 6 countries.
- The CyberSKA portal provides an enhanced forum for collaboration.

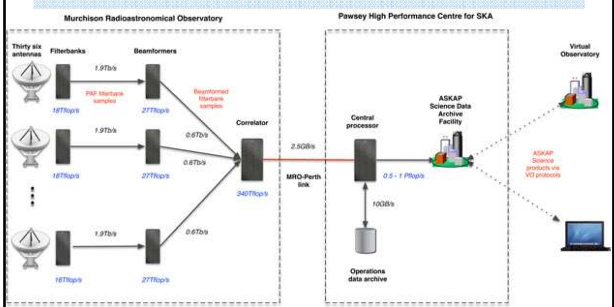
PALFA's membership

Slides from C. Kiddle

What is CyberSKA for PALFA?

- A shared hub for resources
  - Documentation, meeting minutes, publication list, document sharing, task list, …
- An online app centre
  - Candidate viewer, observing sign-up, survey diagnostics, top candidates and known pulsar listing.
  - Single sign-on: Secure and convenient.

ASKAP Data Flow



Prospects for Distributed Processing

- Current telescopes + internet + PCs = pathfinders
- 1.2 billion PCs worldwide
- BOINC platform: Berkeley Open Infrastructure for Network Computing (SETI@Home, Einstein@Home, Astropulse)
- Nereus V: Oxford, open source desktop cloud technology (Newman, Preston)
- Cloud Computing and the Square Kilometre Array (SKA Memo 134, 2011)

Summary

- The era of large surveys:
  - Widefield, wideband, high t/f/θ resolutions
  - Large source numbers, cross-λ studies essential
  - Pathfinders already pushing the envelope
- Science pathfinding ←→ instrumentation dev
  - SKA design is motivated through flowdown from KSPs
  - KSPs have their roots in near-term science continuing to be realized
  - Near-term science results require SKA prototypes on existing telescopes
- Examples:
  - Wideband feeds for precision timing, transients
  - PAFs for high survey speed (HI, continuum, RM, pulsars, transients)
  - Large-N imaging
- "Big data" cyber-infrastructure: driven by current needs, which will be dwarfed by SKA1 and SKA2

Extras

Technical Concept for SKA_1

1) **Low-frequency sparse aperture array** with an A/T_{sys} of up to 2000 m²/K operating at frequencies between 70 and 450 MHz. The array will be centrally condensed but some of the collecting area will be in stations located out to a maximum baseline length of 100 km from the core, and

2) **Dish array with A_{eff}/T_{sys} of up to 1000 m²/K** using approximately two hundred and fifty 15-metre antennas, employing an instrumentation package that will use single-pixel feeds to provide high sensitivity and excellent polarisation characteristics over a frequency range of 0.45-3 GHz. The array will be centrally condensed but some of the elements will be co-located with the sparse aperture array stations out to a maximum baseline length of 100 km from the core.

The dish design will be SKA_2 compliant in terms of its overall performance specification, including a target rms. surface accuracy of 0.5 mm or better.

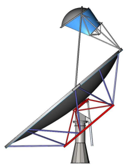
Technical Concept for SKA_1-mid

A dish array with A_{eff}/T_{sys} of up to 1000 m²/K using approximately two hundred and fifty 15-meter antennas, employing an instrumentation package that will use single-pixel feeds to provide high sensitivity and excellent polarisation characteristics over a frequency range of 0.45-3 GHz. The array will be centrally condensed but may extend out to 100 km for auxiliary science

The dish design will be SKA_2 compliant in terms of its overall performance specification, including a target rms. surface accuracy of 0.5 mm or better.

Additional feed antennas would allow SKA_1 to extend to 10 GHz or higher but these are not in the baseline plan

Phase 1 antennas are expected to be offset Gregorian reflectors designed for low-noise and low cost as with the DVA-1 antenna prototype now being designed as part of the TDP and the Dish Verification Program.



Notional Timeline

The technical timeline is as follows:

1. 2010-12: telescope system design, prototyping and costing
2. 2013-15: detailed engineering design & pre-construction phase
3. 2016-19: construction, commissioning & early science observations
4. 2016: Advanced Instrumentation Program (AIP) decision
5. 2020: Full SKA_1 science operations begin

Advanced Instrumentation Program

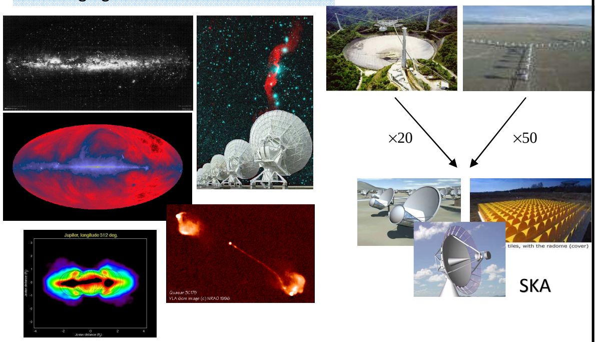
- The Advanced Instrumentation Programme (AIP) will seek to capitalise on investments made by the SKA Organisation and others parties in innovative technology development over the pre-construction period 2011-2015.
- In 2011-2015, advance instrumentation systems under development for the SKA are expected to include:
  - Phased Array Feeds (PAFs),
  - Dense Aperture Arrays (DAA),
  - High frequency feeds
- The AIP will lead to technology choices for SKA_2 as well as provide advanced systems for SKA_1

SKA_2

- Components of SKA_1 will be compliant to SKA_2 requirements
- SKA_1 will serve as a demonstrator for SKA_2 in addition to being an important scientific instrument

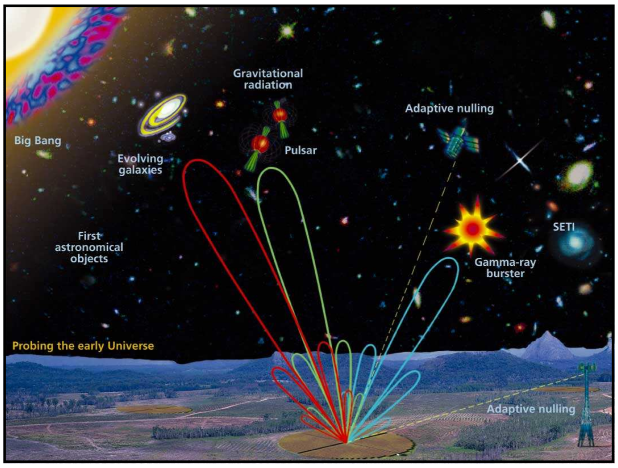
Radio Telescopes:
non-imaging
imaging

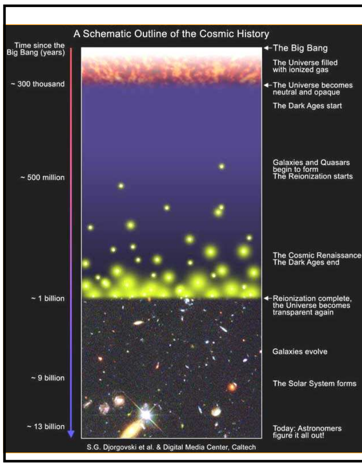
Arecibo VLA



Innovations in Radio Telescopes

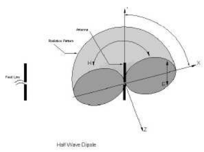
- Where needed?
  - High angular resolution with high sensitivity
  - Wide overall field of view for
    - Fast surveys of the sky (large numbers of objects)
    - Time variable sources (bursts)
- Challenges:
  - Building collecting area cheaply
  - Exploiting Moore's law in digital electronics
  - i.e. steel/aluminum vs. silicon/germanium

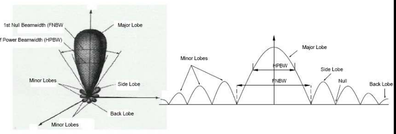




Beam Patterns and Pixels

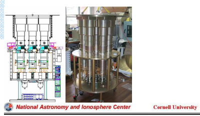
- All telescopes have an angular response to radiation
- Optical/IR/X-ray/Gamma-ray: point spread function (PSF)
- Radio: antenna power pattern $P_n(\theta)$
- A single reflector with a single feed antenna at the focus has one pixel



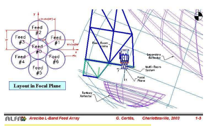


Getting Multiple Pixels

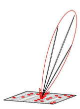
1. Use multiple feed antennas (feed clusters)
   e.g. ALFA = Arecibo L-band Feed Array (7 pixels)



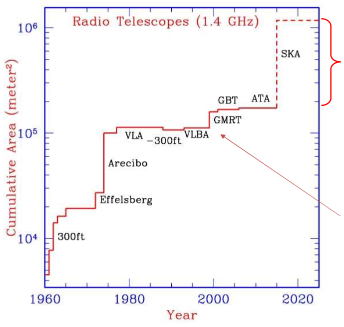
2. Use a phased-array feed system
   Difficult, R&D now a major part of SKA efforts



3. Use arrays of antennas as interferometers and synthesize an aperture



The Collecting Area Plateau in Radio Astronomy



Recent growth in sensitivity has exploited low-noise devices, developments in digital signal processing bandwidth, and calibration and imaging techniques.

Course II: Compact Objects, the Dynamic Radio Sky, and 21st Century Radio Telescope Facilities

Jim Cordes
Professor of Astronomy
Cornell University

Five Lectures:

1. Astrophysics of neutron stars and other compact objects
2. Plasma propagation effects (ISM, IGM, ionosphere)
3. Precision imaging and astrometry
4. The dynamic radio sky (transients and variability)
5. New radio telescope arrays for key science and discovery

Cornell University

- Terzan 45, 47 Tucanae

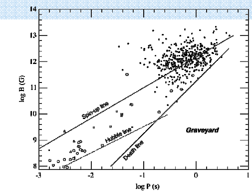


Figure 1. The magnetic fields and periods of known pulsars (see Camilo, this volume for an update). Filled dots indicate isolated pulsars and open circles binaries, both in the galactic disc. Isolated pulsars in globular clusters are shown as triangles and binaries in globular clusters as squares. The spin-up line shows the minimum period to which a neutron star can be spun-up in Eddington-limited accretion. Pulsar activity ceases to the right of the death line, and the spindown age of a pulsar equals 10^{10} y on the Hubble line.

2. Recycling

That the rapid spin of millisecond pulsars may be a result of spin-up due to accretion was conjectured right after the discovery of the first millisecond pulsar B1937+21, which was not even a member of a binary system (Radhakrishnan and Srinivasan 1982). The spin-up process (also called recycling) can achieve a very short spin period if the stellar magnetic field is low, and the accretion rate is high:

Course II Lecture 5

New Radio Telescope Arrays for Key Science and Discovery

- GC pulsars
- Limits on pulsar timing, what needed to mitigate?
  - Assessogram for GW detection
- SKA and SKA precursors
  - KSPs for the SKA
  - Plan for Phase 1
  - ASKAP, MeerKAT