Science with Large Arrays

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Why is radio astronomy important?

Explores fundamental physics using:

- the first photons set free in the universe after the "Big Bang"
- the basic element, hydrogen – the 21cm line
- magnetic fields -- polarisation imaging
- the most accurate clocks in the universe – millisecond pulsars

"Window" on matter in different phases

- synchrotron radiation
- maser emission
- bremsstrahlung from thermal gas

Penetrates dust/gas:

- absorbs & scatters radiation in most other wavebands

Provides highest resolution images at any wavelength - VLBI

Because it provides unique information about the universe

Radio telescopes make discoveries!

Cosmic Microwave Background

Quasars and radio galaxies

Cosmological evolution of radio sources

Drove the astronomical agenda for decades

BUT..the rate of discovery may be slowing down....

How much is this is due to the way in which today's telescopes are used?

- Proposal peer review and small amounts of time aimed at answering known "issues"

→ Need "technology push" not just "applications pull"

A few lessons from 70 years of history

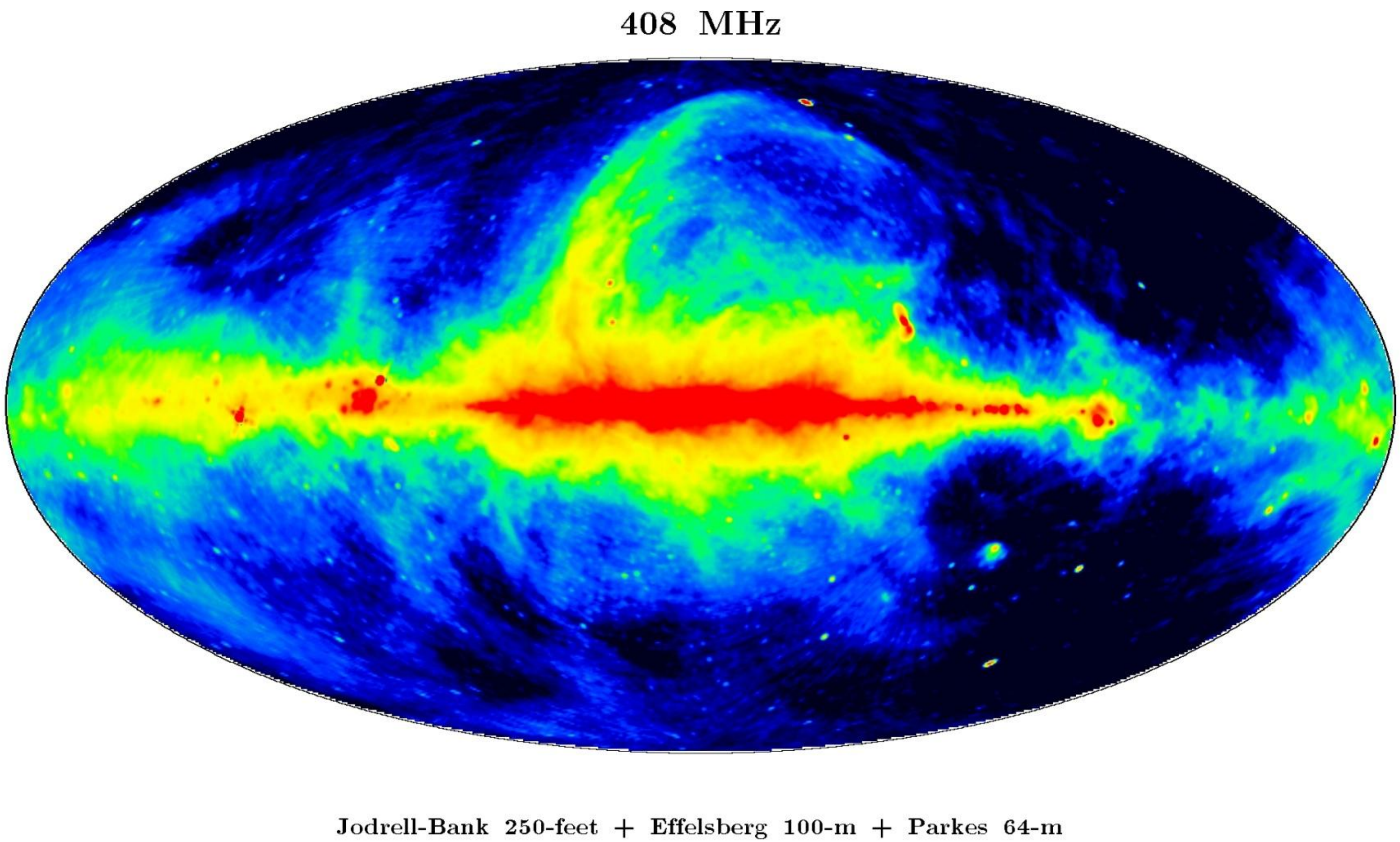
Discovery is unpredictable but can be planned…
by exploring new regions of parameter space:
enabled by technical innovation (Harwit)

→ observations in new areas of phase space
→ more sensitivity & resolution in various domains
→ more sky coverage
→ more patience

Surveying (in many different ways) pays off

Radio telescopes are NOT remembered for the original science motivations of their designers !

The all-sky radio map by Haslam et al.



One of most cited papers in radioastronomy (for subtracting out Galactic synchrotron radiation from the CMBR.)

The CMBR was not even discovered until after the Jodrell Bank and Parkes telescopes came into operation !

Why surveys?

- For opening `discovery space' vs. addressing specific questions

- Survey design often driven by specific science questions, but unforseen collateral science payoffs often more interesting and varied than the original goals:

- Scientific landscape evolves between survey design & execution

Josh Frieman talking about *optical* surveys

Beneficial "unintended consequences"....

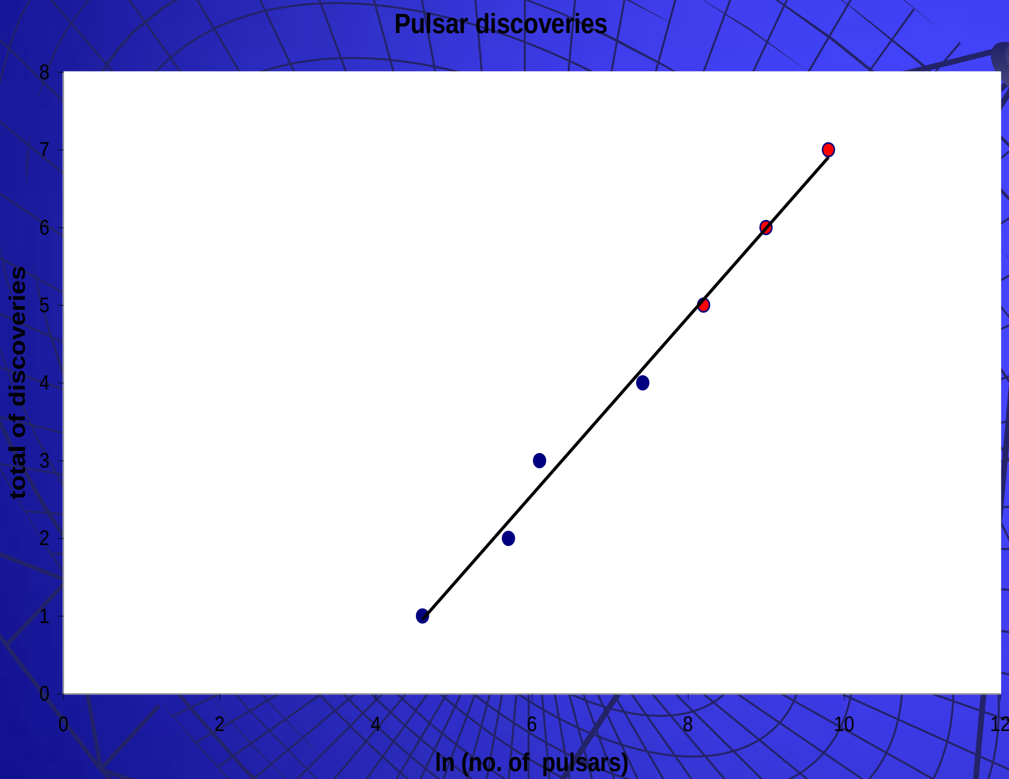
"...one of the most powerful laws in the universe is *the law of unintended consequences.* This applies to school teachers and Realtors and crack dealers as well as expectant mothers, sumo wrestlers, bagel salesmen and the Ku Klux Klan"

Steven D. Levitt & Stephen J. Dubner
"SUPERFREAK-ONOMICS" 2009

plus astronomers and their surveys !

Patience pays off

Amount of "surprise" in a data set rises as the log of the number of independent data elements within it. (Fisher 1943)



	Number of further discoveries	Number of pulsars known	Ln (no. pulsars)
Initial discovery	0		
Binary pulsar	1	100	4.6
Millisec pulsar	2	300	5.7
Planetary system	3	450	6.1
Double pulsar	4	1600	7.4
Next discovery	5	3650	8.2
Next discovery	6	8100	9.0
Next discovery	7	18000	9.8

Cumulative total of major pulsar discoveries against ln (N_{tot})

→ next new phenomenon when the current number of pulsars is doubled ?

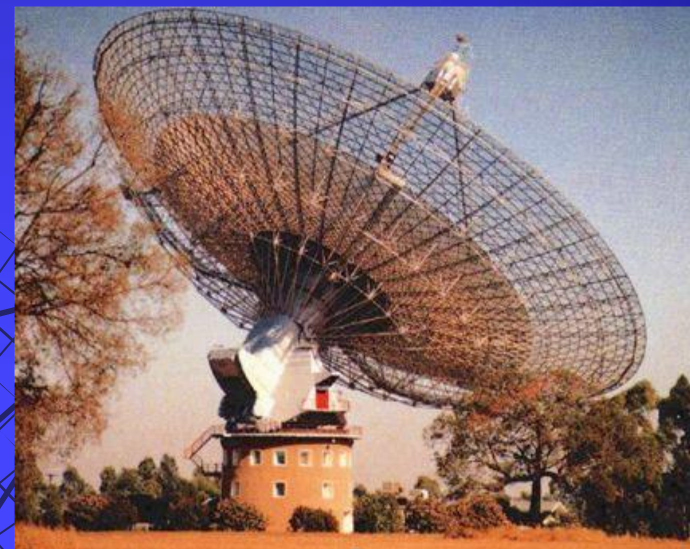
Think out of the box - phase space domains can be linked..

- Intensity
- Temporal
  - slow variations
  - transients
- Spatial
  - small-scale patterns
  - large-scale patterns
- Spectral
  - narrow-band: new lines; variable lines
  - broad-band features

New phenomena may appear at the intersections (Zwicky's "Morphological" approach)

Focal Plane Arrays are science multipliers

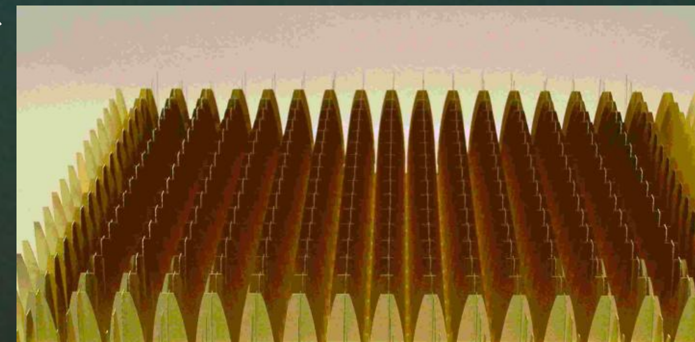
7-beam 5 GHz array in 1980s



13-beam 1.4 GHz array in 1990s

Revitalised the productivity of these mature telescopes by allowing new survey observations

Focal Plane Arrays are science multipliers



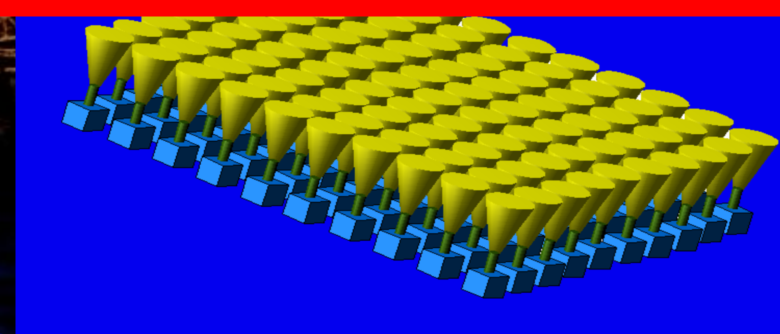
Low-frequency (1.4-5 GHz) beam-forming arrays to maximise the potential of interferometers (WSRT, ASKAP)

In general cover much larger fields than interferometers - provide synoptic views

Science better if can see all scales – not just the bright bits

Large scale environment may set small scale details (as in Kolmogorov turbulence) or vice versa (as in AGNs)

Mid-frequency (15-100 GHz) horn arrays to maximise the potential of large single dishes at low altitude



High frequency (100-1000 GHz) horn (?) arrays to maximise the potential of single dishes at high altitude

The "APRICOT" philosophy

General-purpose radio cameras capable of polarisation-sensitive broad-band continuum and spectroscopic observations at the flick of a switch.

→ surveying speed

→ better data homogeneity by allowing large areas to be covered in similar weather conditions and elevations, thus minimizing calibration uncertainties.

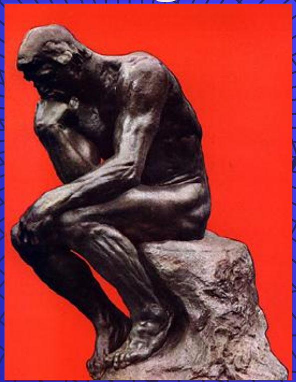
→ same receiver for different types of observation in different weather enhances operational efficiency and user access

Follow up on EVLA or ALMA

Is better technology the only answer?

No! – there is also the human factor

" Discoveries rely very little on blind luck or grand strokes of genius and much more on solid logic, a talent for apt comparison and a mind so steeped in a discipline that it can recognize an unexpected clue for what it's worth".



"In the field of observation chance favours the prepared mind" – Louis Pasteur

Need combination of new technology and patience
AND many people combing through the data archives

So what is the science that large FPAs allow but which we probably won't remember ?

Molecules in The Galaxy

- Star-forming regions & circumstellar envelopes
  - Unbiassed imaging plus modelling → temperature & density
  - Many carbon-chain species in the 30-50 GHz band (HC_nN n=3,5,7; C_nH n=5,6; C_nS n=1,3,5) diagnostic of cold dense quiescent gas
  - Other species:
    - SiO (shock tracer); OCS (sulphur sink)
    - CH_3CN (hot core species); SO (Zeeman sensitive)
    - SiO masers in CSEs close to the star
    - Complex organic species – biologically important precursors

With large format cameras could survey complete clouds in one day

Galactic Continuum

Synoptic surveys of diffuse Galactic emission

Need to dissect out the contributions from
- synchrotron;
- free-free;
- anomalous dust;
- thermal dust

For ISM astrophysics and CMBR polarised foregrounds

In compact regions e.g. YSOs the SED provide diagnostics of dust agglomeration in protoplanetary disks

ISM in high-z galaxies

Key ingredient in galaxy formation and evolution provides the 'fuel' for star formation and SMBH accretion.

High-z ISM studies are in a pioneering stage – every molecular/atomic line detection is a major discovery.

Blind spectroscopic surveys for CO and other high density tracers (HCN HCO+) in gas-rich galaxies

→excitation unbiased view of the high redshift Universe.

→the ISM of the bulk galaxy population might be only be low-to-moderately excited and not seen by high-J observations.

Extragalactic Radio Sources

- Surveys for discrete sources (in polarisation)
  - Find new types of AGN e.g. youngest CSOs
    - follow-up with mm-VLBI & VSOP-2 imaging
    - follow-up of FERMI transients
  - Net of calibration sources for EVLA and mm-VLBI
  - Complement to *Planck* and all high-sensitivity CMBR experiments

- 90-m telescope with 100-pixel FPA could carry out a million source survey i.e. NVSS at 10x the frequency

Cluster surveys via SZE

- Surveys for/of clusters of galaxies via the SZE

- Study of cluster substructures via SZE from:
  - Galaxy motions,
  - Mergers
  - Radio sources
  - Cooling flows
  - etc

The Dynamic Radio Sky

In contrast to optical/X-ray/γ-ray the radio “transient s … y explored

Requires lar … erage x time spent

“Transient” … pulsars) cover a wide range of tim … lensity and will be rare

Several projects planning to observe at long wavelengths (e.g. LOFAR) – but none systematically at centimetre wavelengths

The opportunities…

- Many major discoveries in science were not predicted
- The excitement of new instruments will not be in the old questions which will be answered, but the new questions which will be raised by the new observations they will permit.

For careful surveys with large-format cameras…

The "killer application" is the survey itself

The best-remembered result may be years ahead !

The End

Ruze's field of view estimate

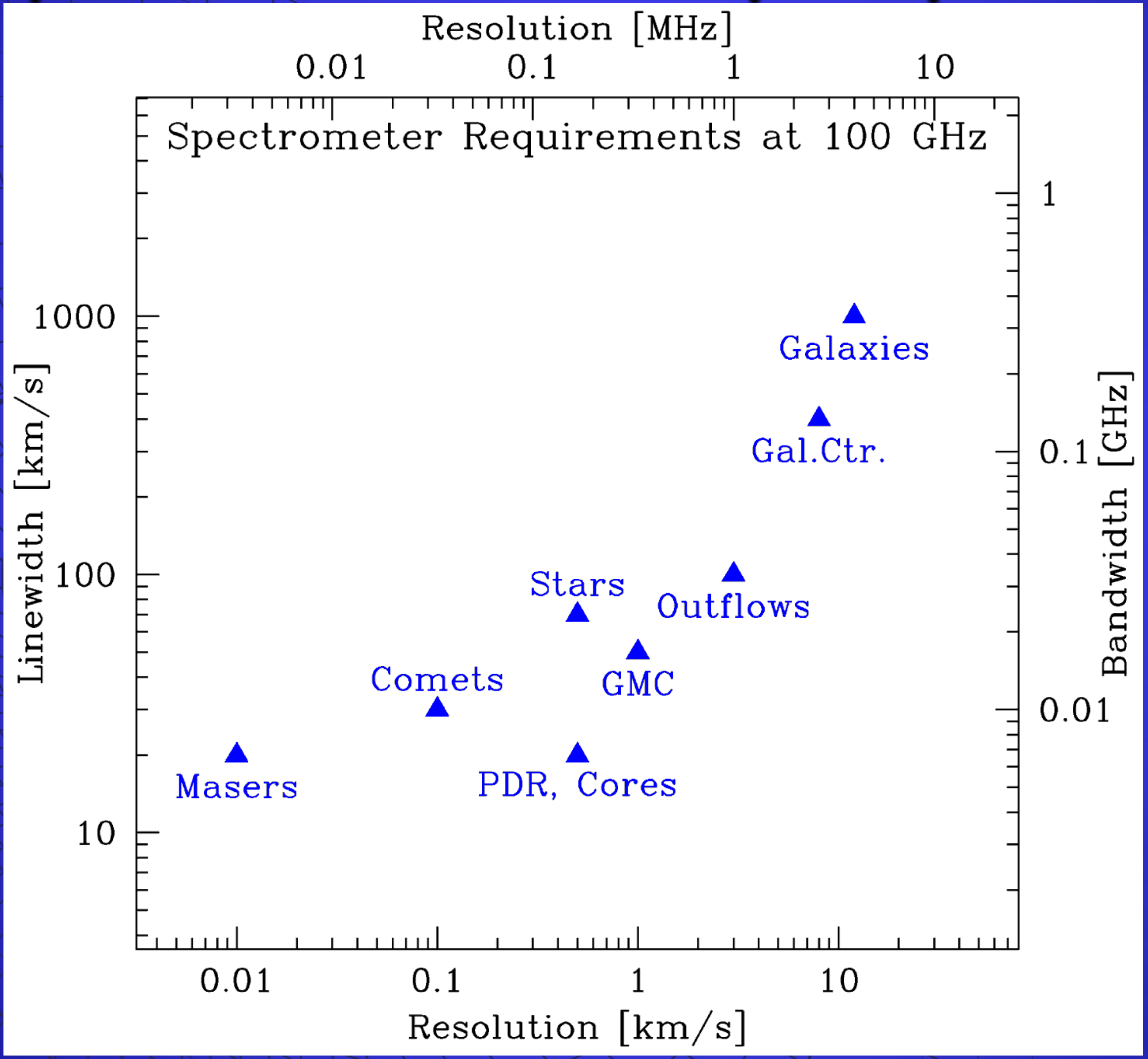
$$\text{Number of FWHM beamwidths} \approx 11\left(\frac{f}{D}\right)^2$$

This is for 1 dB peak gain loss (and coma lobe at –10.5 dB), from fits to computations for 10 dB edge taper and *f/D* = 0.25 to 2.

A 1 kpixel square array has 32x32 elements. Counting the factor 2 in center to center spacing, the distance from the center to the furthest pixel is 45 FWHM beamwidths.

This and Ruze's result implies a minimum *f/D* ratio of 2 for the feed optics – so the *f*/2.5 constraint from the front-end module size is reasonable.

Spectrometer properties



70 years of radio astronomy... what a telescope is "known for" is almost never what it was built for!

- Cosmic radio emission (1930s)
  - Jansky telescope
  - Communication research
- Solar Radio Bursts (1940s)
  - Wartime radar dishes
  - Radar
- Non-thermal cosmic (synchrotron) radiation (1940s)
  - Reber telescope
  - Radio astronomy research
- Discovery of radio galaxies (CygA etc) (1950s)
  - Special purpose interferometers
  - Astrometry
- Cosmological evolution of radio sources (1950s)
  - Cambridge Parabolic Cylinders; Sydney Mills Cross
  - Radio surveys ; Radio surveys

Radio noise storms on Jupiter (1955)

Washington Mills Cross

Radio astronomy

Slow rotation rate of Venus (1962)

Goldstone

Deep space tracking

Very compact radio sources and quasars (AGN) (early1960s)

Jodrell MkI; Parkes 64m

Radio emission from cosmic rays; General purposes

Cosmic Microwave Background (1963)

Holmdel Horn

Communications research

GR time delay by planetary radar (1964)

Arecibo

Ionospheric backscatter

Spin-orbit locking of Mercury (1965)

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Pulsars and their association with Supernovae (late 1960s)

Cambridge 1.8 Hectare array; NRAO 91m

Interplanetary scintillation; General purposes

Dark Matter in Spiral Galaxies (1970s)

Westerbork Synthesis Array

General purposes

Jets and S-luminal Motions in AGN (1970s) and XRBs (1990s)

Cambridge 5km; VLA; VLBI arrays

General purposes; General purposes; General purposes

Interstellar Molecules and GMCs (1970s)

NRAO 12m

Millimetre wave astronomy

Masers and Megamasers (1970s and 1980s)

NRAO 140ft; Arecibo

The sun; Ionospheric backscatter

Gravitational Lenses (1979)

Jodrell Mk1; Mk2; NRAO interferometer

General purposes Astrometry & general purposes

Fundamental astrometric reference frame (1980-1990s)
VLBI arrays
General purposes

Mysterious structures & strong B-fields in Gal. Centre (1990s)
VLA, ATCA
General purposes General purposes

Rotating torus and mass of central object in an AGN (late 1990

VLBA
General purposes

Millisec pulsars & grav. radiation loss in a binary (late 1980s)
Arecibo
Ionospheric backscatter

First extra-solar planetary system (around a pulsar) (1990s)
Arecibo
Ionospheric backscatter

Additions suggested after talk

- Size of GRBs (from scintillation)
- Plate tectonic motions
- Discovery of 21cm line:
- Milky Way as a spiral galaxy and Sun's location
- Coronal Mass ejections ??
- Microscopic-sized atoms – law of QM operation macro-scales (Recomb. Lines at tens of MHz.)
- Double radio sources as powered by jets emanating in galactic nuclei

- SKA is a tool for unborn users!

Discoveries and the telescopes

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