Title: Cosmology and Fundamental Physics with the Square Kilometre Array

Date: Jun 17, 2016  03:50 PM

URL: http://pirsa.org/16060027

Abstract: The Square Kilometre Array (SKA) is a next-generation radio telescope scheduled to commence construction in 2018. The SKA will be one of a small set of billion-dollar facilities that collectively span the electromagnetic spectrum, and will be an order of magnitude more sensitive than any other radio facility. The SKA's extraordinary survey capacity will allow it to map the distribution of galaxies and large-scale structure over an unprecedented cosmic volume, providing superb probes of dark matter, dark energy, neutrino physics, magnetogenesis, non-gaussianity and inflation. In addition, pulsar timing with the SKA will provide precision tests of general relativity in the strong field regime, and should allow us to detect gravitational radiation produced by merging supermassive black holes. In this talk, I will provide an overview of the capabilities and science goals for the SKA, highlighting its unique potential for advancing our understanding of cosmology and fundamental physics.
Cosmology and Fundamental Physics with the Square Kilometre Array

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Canadian SKA Science Director

www.skatelescope.ca
@SKACanada
Fundamental Physics with the Square Kilometre Array

- May 1st-5th, 2017, in Flic-en-Flac, Mauritius
- Topics
  - Cosmology & Dark Energy
  - Cosmic Dawn & Reionisation
  - Dark Matter & Astroparticle Physics
  - Gravity & Gravitational Waves

- Invited speakers include:
  - R. Barkana
  - C. Boehm
  - P. Bull
  - T. Davis
  - S. Nissanke
  - F. Pretorius
  - J. Pritchard
  - J. Silk

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Great Observatories for the coming decades

Optical: TMT, GMT, E-ELT

Infrared: JWST

Millimetre/sub-mm: ALMA

Radio: Square Kilometre Array
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The Square Kilometre Array

- Vision: world’s most powerful radio telescope
  - 10 member countries: AU, CA, CN, IN, IT, NL, NZ, SE, ZA, UK
  - Observers and other participants: BR, DE, ES, FR, JP, KR, MT, PL, PT, RU, US

- 2012: site decision; 2015: final baseline design for SKA1 (first ~10%)
  - “SKA1-Low” in Australia: 130,000 dipoles, 50-350 MHz
  - “SKA1-Mid” in South Africa: 200 dishes, 0.35-14 GHz
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SKA Pathfinders & Timeline

• 2013-2020 : SKA pathfinders
  – Murchison Widefield Array (Australia)
  – MeerKAT (South Africa)
  – Australian SKA Pathfinder (Australia)

• 2018-2023 : SKA1 construction and early science

• 2024 : SKA2 construction begins (~10x SKA1)
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SKA Sites

SKA Australia / New Zealand

SKA South Africa
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A Pristine Radio-Quiet Environment

Sydney
Pop. 4.8 million

Narrabri
(ATCA site)
Pop. 5,900

Murchison Shire
(SKA1-Low site)
Pop. 114
**SKA Science**

- Fundamental Physics with Pulsars
- Cosmology
- Cosmic Magnetism
- Epoch of Reionisation
- The Transient Universe
- The Continuum Universe
- The Hydrogen Universe
- The Cradle of Life & Astrobiology

SKA Organisation, Djorgovski et al., C. Reed NASA / JPL-Caltech / SSC, NASA / Stanford Lockheed-Martin Institute for Space Research’s TRACE team
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Neutron Stars and Pulsars

- Extreme objects in every sense
  - \(10 \times\) nuclear density
  - \(B \sim B_q = 4.4 \times 10^{13}\) Gauss
  - Voltage \(\sim 10^{12}\) V
  - \(F_{EM} = 10^{10} - 10^{-12} F_{grav}\)
  - Superfluid superconductor

- Massive stable flywheels \(\rightarrow\) superb cosmic clocks;
  - e.g., period of PSR B1937+21 on June 17th, 2016 (today):
    \[
P = 0.0015578065601492 \pm 0.00000000000000004\text{ s}
    \]

Slide courtesy of Michael Kramer
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Testing General Relativity

- Experiments made in the solar system provide accurate tests of gravity, but only for weak gravitational fields
- In strong fields, physics may be different
- Compute energy in gravitational field: \( \varepsilon = \frac{E_{\text{gravity}}}{mc^2} \)
- Solar system:
  - \( \varepsilon_{\text{Sun}} \approx 10^{-6} \)
  - \( \varepsilon_{\text{Earth}} \approx 10^{-10} \)
- Neutron star: \( \varepsilon_{\text{NS}} \approx 0.15 \)
- Black hole: \( \varepsilon_{\text{BH}} \approx 0.5 \)

Slide courtesy of Michael Kramer
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Current State of the Art (I)

- The first binary neutron star, PSR B1913+16 (Hulse & Taylor 1974)
- Orbit shrinks by 1 cm per day
- First evidence for gravitational waves

![PSR B1913+16](image)

Michael Kramer

Unseen

- $M_c = 1.39 M_\odot$
- $P_b = 7.8$ h

- $P = 59$ ms
- $M_p = 1.44 M_\odot$
- $e = 0.617$

Weisberg & Huang (2016)
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Current State of the Art (II)

- The double pulsar, PSR J0737-3039A/B (Burgay et al. 2003; Lyne et al. 2004)
- Two pulsars, both detected, in a 2.4-hour orbit, viewed edge on
- Post-Keplerian effects measured:
  - orbital decay
  - advance of periastron
  - Shapiro delay
  - Einstein delay
  - geodetic precession
- Stringent tests of general relativity
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Pulsars with the SKA

- Able to detect every pulsar in Milky Way
- Better sensitivity to timing variations
Pulsars with the SKA

- Able to detect every pulsar in Milky Way
- Better sensitivity to timing variations
- Additional effects expected to be probed:
  - second-order post-Keplerian terms
  - frame dragging (Lense-Thirring)
  - relativistic orbital deformation
  - scalar-tensor theories and gravitational dipole radiation
  - strong equivalence principle
  - time evolution of $G$
  - local Lorentz invariance and local positional invariance
A Pulsar – Black Hole Binary

- The remaining holy grail
  - “A binary pulsar with a black-hole companion has the potential of providing a superb new probe of relativistic gravity. The discriminating power of this probe might supersede all its present and foreseeable competitors...” (Damour & Esposito-Farese 1998)

- Cosmic censorship conjecture:
  \[ \chi \equiv \frac{c S}{GM^2} \leq 1 \]

- No-hair theorem:
  \[ q \equiv \frac{c^4 Q}{G^2 M^3} = -\chi^2 \]
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Gravitational Wave Astronomy (II)

Janssen et al. (2015)
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**Neutron Star Equation of State**

- Neutron star interiors: unparalleled laboratory for nuclear physics, low-temperature physics, QCD, superfluidity
- Equation of state: direct probe of relevant physics; determines merger process and gravitational/neutrino radiation signals
- SKA can give precision data on mass, moment of inertia, maximum spin

Watts et al. (2015)
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**Cosmology with the SKA**

- Unique capabilities of the SKA:
  - 21-cm hydrogen line: can detect neutral gas throughout Universe
  - 3D survey of > 1 billion galaxies over a huge cosmic volume
  - Exquisite measurements of galaxy shapes & diffuse emission
  
  $\rightarrow$ spectacular cosmology machine

- Highlighted experiments
  - baryon acoustic oscillations (BAOs) and intensity mapping
  - weak lensing and cosmic shear
  - synchrotron cosmic web
  - real-time cosmology
  (plus many others ...)

[Image of SKA array and sky map]
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SKA Survey Volume

SKA

Euclid

BOSS

d_Hubble

comoving distance

Roy Maartens
Exploring the Universe with the world’s largest radio telescope

SKA Redshift Reach

Bull (2015)
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**BAOs & Intensity Mapping**

- Standard baryon acoustic oscillations
- Intensity mapping
  - Blind 21-cm hydrogen survey, detects integrated emission from all galaxies
  - like the CMB, but at many redshifts
- Dark Energy equation of state \((w_0, w_a)\)
- Constrain primordial non-gaussianity \((f_{\text{NL}})\)
- GR deviations probed by growth rate \((\gamma)\)

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Abdalla et al. (2015)
Fonseca et al. (2015)
Raccanelli et al. (2015)
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Weak Lensing & Cosmic Shear

- Point spread function fully deterministic
  - precision data on galaxy shapes, for 10 galaxies/arcmin$^2$ over 30,000 deg$^2$
  - higher redshifts than DES, LSST, Euclid
  - polarisation & rotation give intrinsic alignment & shape, reduce systematics
  - precision constraints on $\Omega_m$ and $\sigma_8$

Brown et al. (2015)

Harrison et al. (2016)
The Synchrotron Cosmic Web

- Intergalactic shocks accelerate electrons and amplify magnetic fields (Keshet et al. 2004; Battaglia et al. 2009; Araya-Melo et al. 2012)
  - faint radio synchrotron radiation should trace cosmic filaments
  - direct image of large-scale structure of the Universe
  - direct discriminant between models for origin of cosmic magnetism

Injected fields vs primordial fields (Donnert et al. 2009)

SKA simulation (Vazza et al. 2015)
Real Time Cosmology

- The Universe is expanding
  - redshifts \textit{drift} according to underlying cosmology (Sandage 1962; Loeb 1998)
  - \( \frac{dz}{dt} \approx 10^{-11} \text{ year}^{-1} \), \( \frac{dv}{dt} \approx 10 \text{ mHz year}^{-1} \), \( \frac{dv}{dt} \approx 2 \text{ mm/s year}^{-1} \)
  - peak effect at \( z \sim 0.4-0.6 \); only accessible with SKA
  - stack \( 10^9 \) galaxies: 1% precision in redshift drift after 125 days!

Hans-Rainer Klöckner

Klöckner et al. (2015)
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Additional SKA Cosmology

- GR corrections on ultra-large scales (Camera et al. 2015)
- Non-gaussianity via integrated Sachs-Wolfe effect (Raccanelli et al. 2015)
- Constraints on anisotropic expansion (Schwarz et al. 2015)
- Search for axion-like quintessence (Emami et al. 2016)
- Measurement of cosmic dipole (Schwarz et al. 2015)
- WDM and neutrino masses from dark ages fluctuations (Pritchard et al. 2015)
- Tests of modified gravity (Raccanelli et al. 2011; Zhao et al. 2015)
- 21cm-hydrogen topology as a cosmic ruler (Wang et al. 2015)
Summary

- The SKA will be an amazing physics machine
  - pulsar/BH binary: precision tests of GR
  - pulsar timing array: gravitational waves
  - billion galaxies: GR, Dark Energy, inflation
  - weak lensing: complete census of mass
  - 21-cm galaxies: real-time cosmology

- Will also do some wonderful astrophysics!
  - galaxy evolution, fast radio bursts,
    planet formation, astrobiology, SETI, ...

- Key science teams are forming
  - now is the time to engage
  - join relevant Science Working Groups
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