Synergies between SKA and LSST: the transient sky

M. T. BOTTICELLA

INAF - OSSERVATORIO DI CAPODIMONTE
OUTLINES

• Transient sky in the optical and radio wavelengths
• LSST overview
• TVS projects
• Science questions in common between SKA and LSST
• Science benefits of combining information from SKA and LSST
Multi-messenger Astronomy

and

the advent of synoptic sky surveys
New regimes in observational parameter space

There is still a large range of transient parameter space that has not yet been sampled correlating optical and radio properties.
The Large Synoptic Survey Telescope

Science Drivers

• probing dark energy and dark matter

• exploring the transient and variable universe

• mapping the Milky Way galaxy

• taking an inventory of the Solar System
The Large Synoptic Survey Telescope

- High cadence to discover fast transients
- Large volume to discover rare transients
- Multi-band to measure transient colours
- Longer survey duration (2022-2032)
The Large Synoptic Survey Telescope

- effective aperture of 6.7 m
- FoV 9.6 deg$^2$
- Etendue : 319 m$^2$deg$^2$
The Large Synoptic Survey Telescope

Innovative Optical Design

<table>
<thead>
<tr>
<th>Primary mirror diameter</th>
<th>Field of view</th>
</tr>
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<tbody>
<tr>
<td><strong>8m-class telescope</strong></td>
<td>8 m</td>
</tr>
<tr>
<td></td>
<td>0.2°</td>
</tr>
<tr>
<td><strong>LSST</strong></td>
<td>8.4 m</td>
</tr>
<tr>
<td></td>
<td>3.5°</td>
</tr>
</tbody>
</table>

Full Moon is 0.5°
The Large Synoptic Survey Telescope

3.2 billion-pixel camera
189 16-megapixel silicon detectors arranged on 21 "rafts"

The camera includes a filter-changing mechanism
It is positioned in the middle of the telescope

9.6 deg²
0.2x0.2 arcsec² pix

40 times the size of the full moon
Wide-Deep-Fast  80-90% total time
cover large swaths of sky to faint magnitudes repeatedly at short intervals

Baseline 2018a

18,000 deg$^2$ of sky
30-second visits (pairs of 15-second exposures)
repeated every three to four nights
about 825 visits in 10 years spread over the filters ugrizy

2000 deg$^2$ rapid revisits (40 seconds to 30 minutes)
for very fast transient discovery

Deep Drilling Fields (4.5%)
The LSST community is invited to play a key role in the definition of LSST’s Observing Strategy by submitting white papers to help refine the ‘main survey’ and fully define the use of 10-20% of time expected to be devoted to various ‘mini surveys’ (including the ‘Deep Drilling mini surveys’ and ‘Target of Opportunity’ programs).
Data products

10 million time-domain events per night
a catalogue of 37 billion source (20 billion galaxies 7 billion stars)

Prompt data products are generated continuously every observing night, including both alerts to objects that have changed brightness or position, which are released with 60-second latency, source catalogs derived from difference images and image data products that are released with 24-hour latency.

Data Release data products: will be made available annually as the result of coherent processing of the entire science data set to date. These will include calibrated images, measurements of positions, fluxes, and shapes, variability information, and an appropriate compact description of light curves. The Data Release data products will include a uniform reprocessing of the difference-imaging-based Prompt data products.

User Generated data products: will originate from the community, including project teams. These will be created and stored using suitable Application Programming Interfaces that will be provided by the LSST Data Management System.
The Large Synoptic Survey Telescope

LSST Project
LSST Corporation
LSST Science Collaborations:

Galaxies
Michael Cooper (UC Irvine)
Brant Robertson (University of California, Santa Cruz)

Stars, Milky Way, and Local Volume
John Bochanski (Rider University)
John Gizis (University of Delaware)
Nitya Jacob Kallivayalil (University of Virginia)

Solar System
Megan Schwamb (Gemini Observatory, Northern Operations Center)
David Trilling (Northern Arizona University)

Dark Energy
Eric Gawiser (Rutgers The State University of New Jersey)
Phil Marshall (KIPAC)

Active Galactic Nuclei
Niel Brandt (Pennsylvania State University)

Transients and variable stars
Federica Bianco (New York University)
Rachel Street (LCO)

Strong Lensing
Charles Keeton (Rutgers-The State University of New Jersey)
Aprajita Verma (Oxford University)

Informatics and Statistics
Tom Loredo (Cornell University)
Chad Schafer (Carnegie Mellon University)

LSST data rights can join one or more LSST Science Collaborations
Transients and Variable Stars Science Collaboration

- Fast Transients
- Interacting Binaries
- Magnetically Active Stars
- Microlensing Subgroup
- Multiwavelength Characterization/Counterparts
- Non-degenerate Eruptive Variables
- Pulsating Variables
- Supernovae
- Tidal Disruption Events
- Transiting Planets
<table>
<thead>
<tr>
<th><strong>Galaxies</strong></th>
<th>3 PIs</th>
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<tbody>
<tr>
<td>A. Moretti</td>
<td><em>The high-z AGN and galaxies into the Reionization epoch with LSST</em></td>
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<tr>
<td>A. Bivano</td>
<td><em>Clusters of galaxies as probes of cosmology, dark matter, and the evolution of cosmic structures</em></td>
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<tr>
<td>N. Napolitano</td>
<td><em>Stellar and Dark Matter in galaxies</em></td>
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<tr>
<th><strong>Stars</strong></th>
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<tr>
<td>L. Girardi</td>
<td><em>Galactic and Local Group. archaeology with LSST</em></td>
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<tr>
<td>F. Damiani</td>
<td><em>Star formation and episodic accretion</em></td>
</tr>
<tr>
<td>P. Ventura</td>
<td><em>Multiperiodic phenomena in variable stars</em></td>
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<tr>
<td>L. Magrini</td>
<td><em>Photometric metallicities with LSST data</em></td>
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<tr>
<td>G. Clementini</td>
<td><em>The Gaia-LSST synergy: from pulsating stars and star formation history to WD Planets</em></td>
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<tr>
<td>I. Musella</td>
<td><em>RR Lyrae, Cepheids and LBVs to constrain theory using LSST</em></td>
</tr>
<tr>
<td>G. Bono</td>
<td><em>Stellar Variability: The 3D Structure of the Galactic Spheroid</em></td>
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<tr>
<th><strong>Time Domain Astronomy</strong></th>
<th>5 PIs</th>
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<tbody>
<tr>
<td>E. Brocato</td>
<td><em>The astrophysical sources of gravitational waves</em></td>
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<td>S. Campana</td>
<td><em>Gamma Ray Bursts and Tidal Disruption Events</em></td>
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<tr>
<td>A. Pastorello</td>
<td><em>Studying peculiar supernovae, supernova impostors and stellar mergers with LSST</em></td>
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<td>M. T. Botticella</td>
<td><em>Supernovae Demography and Rates. based on Machine Learning Classification</em></td>
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<tr>
<td>C. Raiteri</td>
<td><em>Active Galactic Nuclei, Fast Radio Bursts and Blazars with LSST</em></td>
</tr>
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</table>

TVS and SKA-CTA PRIN PI Giroletti
LSST and SKA

Several science questions in common between the two projects

- cosmology
- galaxy evolution
- time-domain astrophysics

- monitoring a large sky area
- on the sky over much of the same time-period
- Match between the temporal cadence in the optical bands and time resolution in the radio bands
Incoherent synchrotron emission

- Relatively slow variability
- Brightness temperature limited
- Associated with all explosive events
- Found mainly in image stacks

Coherent emission

- Relatively fast variability
- High brightness temperature
- Often highly polarised
- Sometimes very steep spectra
- Found primarily in beam formed data

Radio Transients

Radio follow-up of optical transients
Search for optical counterpart of radio sources
understanding the physics of known transients
radio follow-up of discoveries in the optical bands

The radio emission from CC SNe is essentially non thermal synchrotron emission from relativistic electrons as CC SNe span more than five orders of magnitude in $L_{\text{peak}}$. $L_{\text{peak}}$ is proportional to $t_{\text{peak}}$. Each SN subtype is located in specific regions. Type Ib/c and IIb SNe seem to have higher blastwave speeds.
understanding the physics of known transients
radio follow-up of discoveries in the optical bands

Radio observations are a powerful tool to constrain the central engine properties and sub-parsec environments of the H-stripped stellar explosions. A combination of both early time and late time coverage is needed.

Bridging the gap between Type Ibc SL SNe and long GRB

Margalit et al 2018
understanding the physics of known transients
radio follow-up of discoveries in the optical bands
understanding the physics of known transients

Radio observations can discriminate between the progenitor models of SNe Ia

No SN Ia has been detected so far in the radio implying a very low density for CSM

\[ \text{M} \_ \text{dot} < 10^{-10} \text{ M}_\odot \text{ yr}^{-1} \quad \text{SD system} \]
\[ \text{M} \_ \text{dot} < 10^{-11} \text{ M}_\odot \text{ yr}^{-1} \quad \text{DD system} \]

SN 2014J \quad M < 7.0 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1}
SN2018pv \quad M < 1.7 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}
SN2016coj \quad M < 2.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}
SN2018gv \quad M < 1.9 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1}

for an assumed wind speed of 100 km/s.

Perez Torres et al 2018
Radio transient classification

The relation between the radio and optical flux densities can be used to classify radio transients.

Stewart et al 2018
Unveiling the optically obscured CC SNe
Comparison between radio and optical CC SN rate in the local Universe
Comparison between SFR and CC SN rates in extreme environments
direct detection of KN, GRBs …

- sky coverage of surveys with adequate sensitivity and time resolution
- strategy that revisits that same sky on multiple occasions
- real-time response and localisation

Good angular resolution (≤ 1 arc sec)
Large field of views (≥10 deg²)
Frequencies around or above 2 GHz
Sensitivity close to the μJy/b level
3-5 visits/yr
\( \Delta t_{\text{cadence}} \sim 90 \text{ d} \)

three visits over a year are enough to reliably detect any new KN in the radio

<table>
<thead>
<tr>
<th>SKA survey</th>
<th>Area (deg²)</th>
<th>rms (μJy beam⁻¹)</th>
<th>Sampled Volume (Gpc³ yr⁻¹)</th>
<th>( N_{\text{det}} ) (Gpc⁻³ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKA1-Mid-A</td>
<td>31000</td>
<td>5.0</td>
<td>1.7 × 10⁻⁴</td>
<td>0.61 ± 0.39</td>
</tr>
<tr>
<td>SKA1-Mid-B</td>
<td>500</td>
<td>0.9</td>
<td>3.6 × 10⁻⁴</td>
<td>0.13 ± 0.09</td>
</tr>
<tr>
<td>SKA1-Mid-C</td>
<td>20</td>
<td>0.24</td>
<td>1.1 × 10⁻⁴</td>
<td>0.04 ± 0.02</td>
</tr>
</tbody>
</table>

Della Valle et al 2018
Optical Rates

All these transients will be discovered in an unbiased way

<table>
<thead>
<tr>
<th>SNe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous red novae</td>
</tr>
<tr>
<td>SNe Ia</td>
</tr>
<tr>
<td>SNe Ia</td>
</tr>
<tr>
<td>SNe II</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Class</th>
<th>$M_v$ (mag)</th>
<th>$\tau^b$ (days)</th>
<th>Universal Rate (UR)</th>
<th>PTF Rate</th>
<th>LSST Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminous red novae</td>
<td>$-9..-13$</td>
<td>$20..60$</td>
<td>$(1..10) \times 10^{-13}$ yr$^{-1}$ L$^{-1}$</td>
<td>$0.5..8$</td>
<td>$80..3400$</td>
</tr>
<tr>
<td>SNe Ia</td>
<td>$-15..-17$</td>
<td>$2..5$</td>
<td>$(0.6..2) \times 10^{-6}$ Mpc$^{-3}$ yr$^{-1}$</td>
<td>$4.25$</td>
<td>$1400..8000$</td>
</tr>
<tr>
<td>SNe Ia</td>
<td>$-17..-19.5$</td>
<td>$30..70$</td>
<td>$3 \times 10^{-5}$ Mpc$^{-3}$ yr$^{-1}$</td>
<td>$700$</td>
<td>$200000^d$</td>
</tr>
<tr>
<td>SNe II</td>
<td>$-15..-20$</td>
<td>$20..300$</td>
<td>$(3..8) \times 10^{-5}$ Mpc$^{-3}$ yr$^{-1}$</td>
<td>$300$</td>
<td>$100000^d$</td>
</tr>
</tbody>
</table>

Transients

- CCSN
- Merger
- Magnetar
- Pulsar
- CV
- AGN

Variables

- SN Ia
- TDE
- SLSN

<table>
<thead>
<tr>
<th>Transient</th>
<th>Before LSST</th>
<th>After LSST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superluminous SNe</td>
<td>~20</td>
<td>~$10^5$</td>
</tr>
<tr>
<td>Tidal Disruption Events</td>
<td>~20</td>
<td>~$10^4$</td>
</tr>
<tr>
<td>Orphan LGRBs/Dirty Fireball</td>
<td>1</td>
<td>≤$10^3$</td>
</tr>
<tr>
<td>Orphan SGRBs/Kilonovae</td>
<td>1</td>
<td>≤$10^2$</td>
</tr>
</tbody>
</table>

The II National Workshop of SKA science and technology
## Radio Rates

<table>
<thead>
<tr>
<th>Class</th>
<th>Rate (deg$^{-2}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN</td>
<td>2.3</td>
<td>Thyagarajan et al. (2011)</td>
</tr>
<tr>
<td>TDE</td>
<td>0.52</td>
<td>Frail et al. (2012)</td>
</tr>
<tr>
<td>GRB afterglow</td>
<td>0.002</td>
<td>Frail et al. (2012)</td>
</tr>
<tr>
<td>SN</td>
<td>0.21</td>
<td>Frail et al. (2012)</td>
</tr>
<tr>
<td>XRB</td>
<td>$2.4 \times 10^{-6}$</td>
<td>Gallo, Fender, &amp; Pooley (2003)</td>
</tr>
<tr>
<td>Dwarf Nova</td>
<td>0.0013</td>
<td>Pretorius &amp; Knigge (2012), Servillat et al. (2011)</td>
</tr>
<tr>
<td>Classical nova</td>
<td>0.0023</td>
<td>Roy et al. (2012)</td>
</tr>
<tr>
<td>RSCVn</td>
<td>0.011</td>
<td>Williams et al. (2013), Fasuta, Micela, &amp; Sciortino (1995), Ottmann &amp; Schmitt (1992)</td>
</tr>
<tr>
<td>Algol</td>
<td>0.002</td>
<td>Duerbeck (1984)</td>
</tr>
<tr>
<td>Faire star</td>
<td>0.0064</td>
<td>Reid, Cruz, &amp; Allen (2007), Osten (2008)</td>
</tr>
<tr>
<td>Magnetic CVs</td>
<td>0.038</td>
<td>Pretorius et al. (2004), Pretorius, Knigge, &amp; Schwope (2013)</td>
</tr>
<tr>
<td>Polars</td>
<td>0.0008</td>
<td>Pretorius &amp; Makai (2014), Pretorius, Knigge, &amp; Schwope (2013)</td>
</tr>
<tr>
<td>Polars + IPs</td>
<td>0.039</td>
<td>–</td>
</tr>
</tbody>
</table>

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The II National Workshop of SKA science and technology

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Metzger et al 2015

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<table>
<thead>
<tr>
<th>Spectral Component</th>
<th>SKA-Expanded</th>
<th>SKA</th>
<th>SKA-Low</th>
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<tr>
<td></td>
<td>2060</td>
<td>1300</td>
<td>1900</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>150</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>12</td>
<td>45</td>
</tr>
</tbody>
</table>

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- **SKA-Expanded**: Represents the expanded sensitivity of the SKA.
- **SKA**: Indicates the standard configuration of the SKA.
- **SKA-Low**: Denotes the low sensitivity mode of the SKA.

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- **Metro**: Represents the 1.3 GHz range.
- **SN Ib/c**: Indicates the SN Ib/c spectral component.
- **TDE Off-Axis**: Denotes the off-axis TDE configuration.
- **TDE On-Axis**: Indicates the on-axis TDE configuration.
- **SNR On-Axis**: Represents the SNR On-Axis spectral component.
- **NSM Magnetar/AIC**: Indicates the NSM Magnetar/AIC spectral component.

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The table above highlights the radio rates for various celestial objects, with references provided for each class. The data is compared across different spectral components and configurations of the SKA.
Precursor project

Together MeerLICHT (optical telescope) and MeerKAT (precursor to SKA) will simultaneously be scanning the Southern Sky

The project involves data fusion of multiple catalogues, source association, radio - optical flux correlation of objects which will provide an input to automated source classification.