Next-generation of optical facilities in the multi-messenger era: the SOXS case

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Transients < 2000

adapted from Kulkarni 2012
Transients $> 2000$

![Graph showing transients and their characteristics](image)
Current transients’ view

- Long GRB afterglows
- Superluminous supernovae
- Tidal disruption flares
- Core-collapse supernovae
- Intermediate luminosity transients
- Luminous red novae
- Classical novae
- Kilonovae
- Short GRB afterglows
- Type Ia explosions
- Ca-rich transients
- ASASSN-15lh
- P60-M82OT-081119
- V1309 Sco
THE problem

ePESSTO makes 17% of ALL transient classification
The current answer

1388 transients classified by PESSTO so far
486 transients are being followed by PESSTO

90 nights/year at the ESO/NTT in La Silla
~30% of ePESSTO+ observing time in classification activities
resolution ~500
17% of overall classifications

resolution ~100
46% of overall classifications
SOXS

ESO call for new instruments at NTT (06/2014)
Proposal submission (02/2015)
SOXS selected by ESO (05/2015) out of 19

Main characteristics

- Broad band spectrograph 350-2000 nm
- $R \approx 4,500$ (4,000-6,000)
- Two arms (UV-VIS + NIR) 350-850 nm + 800-2000 nm
- Acquisition camera to perform photometry ugrizY (3.5′x3.5′, 0.2” pixel)
- S/N~10 spectrum - 1 hr exposure $R_{AB} \approx 20.5$
Institutes from 6 Countries

- Common Path, NIR Spectrograph, Control Software & Electronics, Vacuum and Cryogenics, Detectors control (INAF)
- UV/VIS Spectrograph (Weizmann)
- Acquisition Camera (Millennium Institute of Astrophysics - MAS)
- Calibration Unit (Turku University)
- Data Reduction (Queen’s Un. Belfast)
- Tel Aviv University
- Neils Bohr Institute & Aarhus Univ.
SOXS UV-VIS arm

*Aspheric

Mirror*

CaF$_2$ corrector*

Field flattener

Eff vs lambda

Eff [-]

wavelength [Å]

u
g
r
i

λ(Δλ)

4000
5000
6000
7000
8000
9000
10000

0.4
0.5
0.6
0.7
0.8
SOXS NIR arm

Efficiency vs lambda
UV-VIS

RESOLUTION NIR

Resolution vs wavelength [micron]

FORMAT NIR

mm values and wavelength [Å] for each position.
## Acquisition Camera

<table>
<thead>
<tr>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Field of View (FOV)</strong></td>
</tr>
<tr>
<td>3.5 arcmin x 3.5 arcmin</td>
</tr>
<tr>
<td><strong>Detector wavelength range</strong></td>
</tr>
<tr>
<td>Up to 1.0-1.1micron, with QE&gt;20%</td>
</tr>
<tr>
<td><strong>Filters</strong></td>
</tr>
<tr>
<td>u, g, r, i, z, y (LSST) and V (Johnson)</td>
</tr>
<tr>
<td><strong>Image quality</strong></td>
</tr>
<tr>
<td>Scale &lt; 1 arcsec/pixel</td>
</tr>
<tr>
<td><strong>Detector format</strong></td>
</tr>
<tr>
<td>1k x 1k optimized for NIR QE</td>
</tr>
<tr>
<td><strong>Pixel size</strong></td>
</tr>
<tr>
<td>13 micron</td>
</tr>
<tr>
<td><strong>Frame Rate</strong></td>
</tr>
<tr>
<td>High Frame rate (up to 5MHz )</td>
</tr>
<tr>
<td><strong>Readout noise</strong></td>
</tr>
<tr>
<td>Low read out noise (3.0e-)</td>
</tr>
<tr>
<td><strong>Volume</strong></td>
</tr>
<tr>
<td>600mm x 340mm x 393 mm</td>
</tr>
<tr>
<td><strong>Back focal plane</strong></td>
</tr>
<tr>
<td>500mm</td>
</tr>
<tr>
<td><strong>Position</strong></td>
</tr>
<tr>
<td>Close to the Nasmyth flange/ at least 110mm from the optical axis</td>
</tr>
<tr>
<td><strong>Design</strong></td>
</tr>
<tr>
<td>Based on Xshooter A&amp;G</td>
</tr>
</tbody>
</table>
Acquisition Camera

- Andor iKon M-934
- CCD sensor BEX2-DD (Broad band coverage and higher NIR-QE)

<table>
<thead>
<tr>
<th>LSST Band (Wav)</th>
<th>1 sec</th>
<th>2 sec</th>
<th>3 sec</th>
<th>5 sec</th>
<th>10 sec</th>
<th>15 sec</th>
<th>20 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>u' (355.7nm)</td>
<td>15.9</td>
<td>16.7</td>
<td>17.5</td>
<td>17.7</td>
<td>18.4</td>
<td>18.7</td>
<td>19.1</td>
</tr>
<tr>
<td>g' (482.5nm)</td>
<td>18.2</td>
<td>18.9</td>
<td>19.4</td>
<td>19.8</td>
<td>20.5</td>
<td>20.8</td>
<td>21.0</td>
</tr>
<tr>
<td>r' (626.1nm)</td>
<td>18.0</td>
<td>18.6</td>
<td>19.0</td>
<td>19.5</td>
<td>20.0</td>
<td>20.3</td>
<td>20.4</td>
</tr>
<tr>
<td>I' (767.2nm)</td>
<td>16.4</td>
<td>17.1</td>
<td>17.5</td>
<td>17.9</td>
<td>18.4</td>
<td>18.6</td>
<td>18.8</td>
</tr>
<tr>
<td>z' (909.7nm)</td>
<td>15.3</td>
<td>15.9</td>
<td>16.2</td>
<td>16.5</td>
<td>16.9</td>
<td>17.2</td>
<td>17.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VIMOS Band (Wav)</th>
<th>1 sec</th>
<th>2 sec</th>
<th>3 sec</th>
<th>5 sec</th>
<th>10 sec</th>
<th>15 sec</th>
<th>20 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (550nm)</td>
<td>19.5</td>
<td>20.1</td>
<td>20.5</td>
<td>21.0</td>
<td>21.5</td>
<td>21.8</td>
<td>21.9</td>
</tr>
</tbody>
</table>
Calibration Unit

- QTH, penrays, each uses 1 port
- D2 + ThAr occupy 1 port
- → COTS 4-port sphere (Labsphere)
- cable feedthrough at bottom side, ventilation grills
- cover + hinge for easy lamp access, with interlock
SOXS pipeline

• Pixel detrending – bias, flat, dark, linearity corrections (dark only for NIR)
• Produce 2D distortion corrected, orders merged pre-extraction spectrum for each arm (rectification)
• X-shooter like reduction recipes and data products
• But faster production of science ready products

SoXS pipeline will be public

Pipeline also for the acquisition camera data; astrometric and photometric corrections with Pan-STARSS

Very quick. Data reduction in near-real time. No need for a quicklook.
### SOXS timeline & operations

<table>
<thead>
<tr>
<th>Project Phase</th>
<th>Start</th>
<th>End</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary Design</td>
<td>08/2016</td>
<td>07/2017</td>
<td>12 months</td>
</tr>
<tr>
<td>Final Design</td>
<td>08/2017</td>
<td>10/2018</td>
<td>14 months</td>
</tr>
<tr>
<td>MAIT &amp; PAE</td>
<td>11/2018</td>
<td>02/2021</td>
<td>27 months</td>
</tr>
<tr>
<td>Commissioning &amp; PAC (Chile)</td>
<td>03/2021</td>
<td>09/2021</td>
<td>7 months</td>
</tr>
<tr>
<td>Operations</td>
<td>2021</td>
<td>2026</td>
<td></td>
</tr>
</tbody>
</table>
Building SOXS

1. Procurement + SOW
2. Pre sub-system integration = tests on components + facilities
3. Sub-system integration and tests
4. Assembly Readiness Review
5. European System integration and tests
6. System integration and tests @ NTT
Cui protest?

SOXS Consortium time 180 night/yr for 5 years at the NTT

All SOXS Consortium observing time is dedicated to observation of transient and variable sources
Consortium Structure

- E. Cappellaro (INAF-OAPadova) - Italy
- I. Arcavi (Tel Aviv University) - Israel
- M. Della Valle (INAF-OANapoli) - Italy
- S. Mattila (FINCA) - Finland
- A. Gal-Yam (Weizmann) - Israel
- S. Smartt (Univ. Belfast) - UK
- S. Campana (INAF-OABrera) - Italy
Responsibilities

INAF ~ 49% (CP, NIR-arm, integration, management, etc.)
Wiezmann ~24% (UV-VIS arm optics and mechanics)
QUB ~8% (VIS-CCD, reduction pipeline)
FINCA ~7% (Calibration Unit)
MAS ~6% (Acquisition camera)
Tel Aviv University ~4%
DAWN & Aarhus Univ. ~2%
SOXS peculiarities

SOXS is an instrument dedicated to the study of transient and variable sources. Some of them are predictable (eclipses, transits, periodic variability), some others have long reaction times (from days to weeks, SN, blazar variability monitoring, binary X-ray transients), but other need fast reaction times, within one night or less.

SOXS will therefore be based on 180n/yr of Target of Opportunity (ToO) observations!
Integrated approach

SOXS Consortium will manage the entire schedule including ‘SOXS’ time and ‘ESO’ time.

Schedule day-by-day, optimising for into account the Moon, airmass, seeing, water vapour, sky brightness, wind direction constraints. **One SoXS scientist always on duty.**

Possibility to change the observing schedule on the fly.

Overall balance among ESO and SOXS time in terms of dark-grey-bright time, water vapour, seeing, etc.
After an initial period of training (of people) and instrument (set up and debug), no SOXS scientists will be in La Silla (unless for limited periods).

SOXS people
- will prepare the night schedule in advance
- one scientist will remain on-call for problems and for changing the schedule in case of unforeseen fast-track events

ESO people
- observations are carried out by the night operator at the NTT telescope
Data management

Data will be first processed on the mountain with the SOXS pipeline and simultaneously transferred to the ESO archive in Garching (10 min). Data processing should be very quick. Quick look on the mountain.

Standard 2D & 1D spectra will be available.

SOXS people will look only at SOXS Consortium data.

Data will be fully compliant with ESO standard.

Data reduction pipeline will be public.
Data policy

SOXS-GTO sources selected with clear triggering criteria. Criteria will be made public before the start of the operations (and updated every 6 months).

Consortium GTO data will remain private for 12 months (or when data are published).

SOXS will also take classification spectra of sources from optical surveys (up to 25% of SoXS GTO observing time). These data can be claimed by the SOXS Consortium within 3 days, if they fall under a GTO proposal (and will then remain private for 12 months). Otherwise classification data are public.
Why do we need SOXS

Current & new optical survey: ASAS-SN, ATLAS, DES, ZTF, LSST, ...
Space optical missions: Gaia, EUCLID, ...
Space high-energy missions: Swift, Fermi, eROSITA, SVOM, ...
Radio new facilities: MeerKAT, SKA, ...
VHE: MAGIC, HESS, CTA
Messengers: LIGO-Virgo, KM3Net, ANTARES, ...

SOXS@NTT will have 180 n/yr (for 5 yr)
~3,000 - 4,000 spectra/yr
SOXS Science cases

- Classification (service)
- SN (all flavours)
- GW & $\nu$
- TDE & Nuclear transients
- GRB & FRB
- X-ray binaries & magnetars
- Novae & WDs
- Asteroids & Comets
- Young Stellar Objects & Stars
- Blazars & AGN
- Unknown

- Rapid follow-up
- Dense monitoring
What can SOXS do?

First, we will have broad measurements with broad lines superimposed, which were not yet identified, but will allow us to monitor events similar to the death of massive stars and, if close enough, a supernova is virtually always observed.

The construction and operations of SOXS are already fully secured. Without this grant, data will be taken just incidental, turned out to have a hectic pace.

GW counterpart observations were de- served in concomitance. Short duration GRB signals were associated in time with broad lines superimposed, which were not yet identified, but will allow us to monitor events similar to the death of massive stars and, if close enough, a supernova is virtually always observed.

The advanced electromagnetic counterparts in flux are associated with the event of AT2017gfo identified, but likely the rate of events involving at least one neutron star is probably needed.

This testifies to produce breakthrough science in physics in such an extreme ambient and a very fast evolution from a blue (T~10,000 K) to a red (T~6,500 K) supergiant.

What can SOXS do?

K) emission band spectra taken with the X-shooter instrument at the VLT in Chile to first assess its nature. This testifies to produce breakthrough science in physics in such an extreme ambient and a very fast evolution from a blue (T~10,000 K) to a red (T~6,500 K) supergiant.

Here I propose to build and lead a dedicated science team at the Brera Observatory on SOXS with 1 hr (0.5 d) or 2 hr (1.0 d) observations (airmass 1.5, with performance guarantees).

SOXS for GW sources
Shock break out

GRB 060218/SN2006aj
Summary

- SoXS @ NTT from 2021 (5yr)
- Medium resolution (~4,500)
- Broad-band (350-2000 nm)
- Photometry ugrizY (3.5’x3.5’)
- 180 n/yr for 5 years
- Possibility to trigger every night
- Fast reaction, 10min on source
- GTO is fully dedicated to transient and variable sources (~18,000 pointed observations of transients)
Thanks