THE LUVOIR ULTRAVIOLET MULTI-OBJECT SPECTROGRAPH (LUMOS): INSTRUMENT DESIGN AND PERFORMANCE

Kevin France
University of Colorado

POLLUX Team Meeting
Marseille - 9 October 2017
Why it's hard to be a Kevin in France

What happens when you have a name that seems perfectly reasonable in your home country, but raises a sympathetic smile when you're abroad? BBC Europe Correspondent Kevin Connolly has been finding out the hard way.

There is a theory called nominative determinism, much beloved of students of literature and other idlers. It holds that your character will come over time to match your name.
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Leonidas Moustakas (JPL),
John O’Meara (St. Michael’s),
Ilaria Pascucci (Arizona),
Jane Rigby (GSFC),
David Schiminovich (Columbia),
Jason Tumlinson (STScI)
Part 1: LUVOIR Update

LUMOS: The LUVOIR Ultraviolet Multi-Object Spectrograph

- HST 2.4 m
- JWST 6.5 m
- LUVOIR 16 m
<table>
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<tr>
<th>Instrument</th>
<th>Wavelength Range (nm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>HDI</td>
<td>200 – 2400</td>
<td>Imaging and grism spectroscopy</td>
</tr>
<tr>
<td>LUMOS</td>
<td>100 – 400</td>
<td>Imaging and spectroscopy</td>
</tr>
<tr>
<td>ONIRS</td>
<td>400 – 2400</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>coronagraph</td>
<td>vis/NIR (200-1800nm)</td>
<td>High-contrast imaging and spectroscopy</td>
</tr>
<tr>
<td>POLLUX</td>
<td>UV</td>
<td>High-resolution spectropolarimetry</td>
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</tbody>
</table>
LUVOIR UPDATES – Face-to-Face Meeting 6

The 6th LUVOIR STDT F2F Meeting was held in Boulder, CO last week (Oct 5 & 6)

- Telescope Update
- Instrument Update
- Programmatic Update
LUVOIR UPDATES – Face-to-Face Meeting 6

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Telescope update:

- Architecture B – 9.3m R-C
- 54 m² collecting area, 7.7m filled area
- Current size fits in 5m rocket fairing (Delta IV Heavy), but mass requirements* still above 10,000 kg spec
- Pursuing 12,500 kg launch capability
- Laser metrology for segment alignment/control

*preliminary
The 6th LUVOIR STDT F2F Meeting was held in Boulder, CO last week (Oct 5 & 6)

Telescope update:

- Architecture A – 15.1m TMA
- Coronagraph + telescope throughput too low to achieve all exoplanet science goals
- Redesign of Architecture A as a 2-bounce R-C design with all instruments at Cassegrain focal surface
- Central obscuration will decrease, segments may be altered slightly, likely faster system (f/20 → f/12)
LUVOIR UPDATES – Face-to-Face Meeting 6

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Instrument update:

- Coronagraph renamed Extreme Coronagraph for Living Planetary Systems (ECLIPS)
- ECLIPS-A will preserve 3 bands 200-1800nm, ECLIPS-B: 410-1800nm + R~150-200 IFS (each with a vis + NIR channel), and an R = 800 mode
- Both ECLIPS will consider vector vortex coronagraph
- Various efficiency enhancements over original coronagraph: beam-splitters → drop-in flip mirrors, Ag-coatings internal, fiber spectrograph → IFU
LUVOIR UPDATES – Face-to-Face Meeting 6

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Instrument update:

- LUMOS and HDI will change with new Arch.-A, but performance should be comparable (possibly better in some metrics)
- ONIRS study is discontinued, capabilities will be split into LUMOS (R ~15,000 vis MOS, 400-1000nm) and ECLIPS (R = TBD, NIR)
- New wavefront for all instruments (Including POLLUX)
LUMOS: The LUVOIR Ultraviolet Multi-Object Spectrograph

October 8, 2017

LUVOIR UPDATES – Face-to-Face Meeting 6

The 6th LUVOIR STDT F2F Meeting was held in Boulder, CO last week (Oct 5 & 6)

Programmatic update:

- All 4 mission studies have requested an extension on the interim report. NASA agrees, ~3 month extension tentatively approved
- Support for Ball Aerospace to carry out HDI redesign
- New Goddard IDL (Instrument design lab) runs for coronagraph, LUMOS, and HDI in late-2017 to mid-2018
The LUVOIR instruments

Europa jets observed with HST

Roth et al. (2014)

Z = 2 galaxy
The LUVOIR instruments: Oct 6th

**HDI** – 200 – 2400 nm imaging and grism spectroscopy

**LUMOS** – 100 – 400 nm imaging and spectroscopy

**ONIRS** – 400 – 2400 nm spectroscopy

**ECLIPS** – vis/NIR high-contrast imaging and spectroscopy

**POLLUX** – UV high-resolution spectropolarimetry

Europa jets observed with 15-m LUVOIR

Credit: G. Ballester (LPL)
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**POLLUX** – UV high-resolution spectropolarimetry

Europa jets observed with 15-m LUVOIR

Credit: G. Ballester (LPL)
Part 2: LUMOS (Design team – Colorado, Engineering team – GSFC)

One of the three primary instruments voted on by the STDT at the second face-to-face meeting at Goddard in Aug 2016 (w/ HDI, coronagraph)

- First design for Architecture A (15m) complete
- Instrument Design Lab run (GSFC), May 15-19 2017
- LUMOS team has its own technology gap list, collaboration on development programs

“LUMOS-B” for 9m Architecture B beginning

- R-C telescope, longer instrument bay
- Mass constraints may require descope
- Plan is to make scalable from new 15m version
LUVOIR astrophysics science drivers

• Characterizing the gas phase of the cosmos:
  • IGM, CGM – H I, CIII, C IV, O VI, Ne VIII
  • ISM, Galaxies – Si II, Mg II, C II, C I, H, D, H₂, HD
  • PPDs – C IV, H₂, CO, H₂O, CO₂, OH, CH₄
  • Exoplanet atmospheric and exospheric markers - H I, O I, C II, OH, O₂, O₃, H₂

• All of these are well-traced (often best-traced) in the UV
• CGM, galaxies, disks are often extended objects.
• QSO tomography and disks require high velocity resolution
• Lyman Continuum and other low-brightness sources require large statistics
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- All of these are well-traced (often best-traced) in the UV (100 – 400nm)
- CGM, galaxies, disks are often extended objects. (imaging, multi-object spec)
- QSO tomography and disks require high velocity resolution (med/high-res)
- Lyman Continuum and other low-brightness sources require large statistics (high throughput, multi-object spec)

LUMOS requires multi-object, wide-field imaging spectroscopy capability with both high and low resolution modes, with sensitivity into the Lyman UV (at least to 100 nm).
LUMOS Instrument Bay

- HST: 4.5 m²
- LUVOIR (Arch A): 134.8 m²
- LUVOIR (Arch B): ~54 m²

Aperture Ratio = 134.8 m²/4.5 m² ≈ 30x
LUMOS Structure and Mechanical

LUMOS Truss Enclosure (LTE);
mounted with flexures to Optical Bench;
composed of two halves;
square tubes (carbon composite)

170 K Radiator;
mounted to LTE;
alum. HC and facesheets

Graduate research assistant storage area

Electronics Radiator;
mounted to LTE;
alum. HC and facesheets
LUVOIR
15-m Focal Plane (will change)
LUMOS: MOS channels (FUV and NUV)

Micro-shutter Array (located at OTE focal plane)

From OTE

MOS Relay Mirror (MRM) 1

NUV G300M
FUV G145LL
FUV G155L
FUV G120M
FUV G150M
FUV G180M

NUV MRM3

PTT Mech.

MOS FUV Focal Plane Array

TT Mech.

MOS NUV Focal Plane Array

MOS Relay Mirror (MRM) 2
## LUMOS: Specs and Performance

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<th>FUV MOS and Imager MCP</th>
<th>NUV MOS CMOS</th>
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<td>100 x 200 um (pitch)</td>
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<td>Elements per Tile</td>
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<td>Tiles per Array</td>
<td>3 x 2</td>
<td>2 x 2 (Imager 1)</td>
<td>7 x 3</td>
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<td>Detector Tile Dimensions</td>
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<tr>
<td>Detector Package</td>
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- Gratings: HST COS (Heritage)
- MCP QE: HST COS, O. Siegmund
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Particle Background Reduction

The particle background at L2 is 3 – 5 times that in LEO. (!)
Measured by LRO-LAMP, interplanetary coast on ALICE spectrographs

This will dominate the Background Equivalent Flux (BEF) for the open-face MCPs and limit faint object spectroscopy, especially for extended objects.

We are adopting two strategies to mitigate the background:

ALD/Borosilicate glass plates, reduce sensitivity to MeV gamma-rays by ~2 – 3 (~5 – 10 times lower dark rates in lab total)

(Anti-) Coincident detection/rejection
Particle Background Reduction

Very low MCP background (~0.03 cm\(^{-2}\) sec\(^{-1}\)) is achievable with ALD MCPs. But having intrinsically low MCP background is not enough. It is often the case that the local high energy particle & gamma rates dominate.

The timing resolution with photon counting MCP detectors is at the 100ps level. High energy particle events look like single events and can be discriminated with high efficiency by amplitude rejection and by timing coincidence. A combination of radiation shielding, amplitude thresholding, coincidence timing rejection and intrinsically low background / gamma sensitivity could make background improvements of an order of magnitude.

Illustration of the anti-coincidence shield flown on the EURD instrument in 1997. 85% rejection of muon events in ground tests, MCP background rate ~0.06 cm\(^{-2}\) sec\(^{-1}\) (Bowyer et al 1997).

Slide from Ossy Siegmund – UC Berkeley
LUMOS Performance

![Graph showing LUMOS Performance with wavelength (Å) on the x-axis and effective area (cm²) on the y-axis. The graph compares G155L and G300M.]
LUMOS Performance

Background Equivalent Flux
(erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$)

Wavelength (Å)

S/N per resolution element

$T_{\text{exp}} = 18000s$

- $F_\lambda (1200Å), G120M$
- $F_\lambda (2500Å), G300M$
- $F_\lambda (1200Å), G145LL$

$F_\lambda (1200Å), \text{COS G130M}$
LUMOS Performance**

- \( R \geq HST-COS \) everywhere in FOV
  - Meets STDT spectral resolution spec over > 80% of the FOV
  - Extended source \( R \sim 1/6 \) point source \( R \) for filled slit
  - \(~1200\) shutters available per exposure in M & L modes
    - \((\sim 10,000\) for G145LL)\)

- Angular resolution < STDT spec for 95% of the FOV
- Each microshutter is \( \sim110\) mas (clear) in height, so each is a “long slit” aperture (\(\sim4\)-10 XD resols/shutter).

**(Figures represent the average over the bandpass, not the peak)
LUMOS High-Resolution Channel: E135H

- OTE Focal Plane
- High-Res Relay Mirror (HRM1)
- From OTE
- HRMM (Me7)
- E135 H
- HRS Cross-Disperser
- HRS FUV
- FEE
- HRS FUV Detector (MCP-CsI)
Mechanically ruled baseline (~90 gr/mm). TRL 7. **Holographic or ion-etched upgrade desired** (TRL 2)

100mm x 100mm Cross-strip anode TRL 5

Toroidally figured low-line density (~350 gr/mm). J-Y. TRL 7
LUMOS High-Resolution Performance

- $R > 100,000$ over 1000 – 1600 Å bandpass
- Peak $A_{\text{eff}} \approx 45,000 \text{ cm}^2$ (throughput $\sim 4.5 \times \text{STIS E140H}$)
- $\text{BEF} \approx 5 \times 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ (ignoring echelle scatter)
LUMOS High-Resolution Performance

Prototypical Observation:

$F_\lambda \approx 1 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$
to $S/N = 25$/resel in 5 hours

HST Comparison:

1) HST-COS @ $R = 17,000$
   $T_{\text{exp}} = 76$ ks

2) HST-STIS @ $R = 114,000$
   $T_{\text{exp}} = 150$ Ms ($\sim 5$ yr)
POLLUX Science Requirements

- SNR=10 for flux $10^{-17}$ erg/s/cm² in the NV line (124 nm) in a brown dwarf within 40 pc and dispersion 100,000 in 10,000 seconds

LUMOS HRS: SNR = 16.8
POLLUX Science Requirements

- SNR=10 for flux 1e-17 erg/s/cm² in the NV line (124 nm) in a brown dwarf within 40 pc and dispersion 100,000 in 10,000 seconds

  LUMOS HRS: SNR = 16.8

- S/N per resolution element of 100** integrating for 1 hour a flux of 10^-14 erg cm^-2 s^-1 Å^-1  (**fixed pattern noise significant for S/N > 50 / resol)

  LUMOS HRS: SNR = 35
LUMOS FUV Imager
**LUMOS Performance**

**FUV Imager Spot Sizes:**

Detector-limited 12.6 mas imaging over the entire FOV

Multi-layer filters have ~ 85% peak reflection in band, ~ 1% out of band (Rodreguez-De Marcos et al. 2016)

Crossover mode images MSA through Imaging system for targeting and field screening (no band filters, but ND filters included for BOP)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Bandpass</th>
</tr>
</thead>
<tbody>
<tr>
<td>F110M</td>
<td>102 – 118 nm</td>
</tr>
<tr>
<td>F140M</td>
<td>130 – 150 nm</td>
</tr>
<tr>
<td>F160M</td>
<td>150 – 170 nm</td>
</tr>
<tr>
<td>G180M</td>
<td>170 – 190 nm</td>
</tr>
<tr>
<td>F150W</td>
<td>135 – 175 nm</td>
</tr>
<tr>
<td>Open</td>
<td>100 – 200 nm</td>
</tr>
<tr>
<td>“GALEX FUV”</td>
<td>~ 135 – 200 nm</td>
</tr>
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power, bandpass, and angular resolution boxes, the target value is on top, the average value at the center of the field delivered by the LUMOS design is beneath in bold and parentheses, and the average parameter value over 80% of the imaging field-of-view is beneath in bold, italics, and parentheses. The lower number demonstrates that LUMOS achieves the spectral and spatial resolution goals across the majority of its spectral and spatial detector area.

## LUMOS Performance Summary

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<th>G155L</th>
<th>G145LL</th>
<th>G300M</th>
<th>FUV Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Resolving Power</td>
<td>30,000</td>
<td>30,000</td>
<td>30,000</td>
<td>8,000</td>
<td>500</td>
<td>30,000</td>
<td>Avg, cen of FOV</td>
</tr>
<tr>
<td>(42,000) (30,300)</td>
<td>(54,500) (37,750)</td>
<td>(63,200) (40,750)</td>
<td>(16,000) (11,550)</td>
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<td>(40,600)</td>
<td>(28,000)</td>
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<tr>
<td>Optimized Spectral Bandpass (Total)</td>
<td>100 – 140nm (92.5 – 147.4 nm)</td>
<td>130 – 170nm (123.4 – 176.6 nm)</td>
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<td>Angular Resolution</td>
<td>50 mas (11 mas) (17 mas)</td>
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<td>25 mas (12.6 mas) (12.6 mas)</td>
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<tr>
<td>Temporal Resolution</td>
<td>1 msec</td>
<td>1 msec</td>
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<td>1 sec</td>
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<tr>
<td>Peak Throughput</td>
<td>5%</td>
<td>5%</td>
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<td>5%</td>
<td>5%</td>
<td>5%</td>
<td>10%</td>
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<td>Field of View</td>
<td>2' × 2' (3' × 1.6')</td>
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LUMOS Target Acquisition and BOP
LUMOS MOS Example Science Program #1: Surveying the Birthplace of Planets
LUMOS MOS Example Science Program
Surveying the Birthplace of Planets

- Map 5 regions in Orion from 1 – 10 Myr, 10s – 100s Myr, protoplanetary disks in each
- Every target field would return more data than all previous HST UV observations of disks combined
- Initial abundances for planetary atmospheres
- Influence of external stars
- Radial distribution of protoplanetary gas as a function of time
LUMOS MOS Example Science Program #2:
Lyman Continuum Luminosity Function Evolution 0.1 < z < 1.2

- ~600 ionizing radiation detections from 0 < z < 1.2 galaxies to $f_{\text{esc}} = 1\%$
- > 100x current, contested sample
- $f_{\text{esc}}(z)$
LUVOIR online simulation tools

http://asd.gsfc.nasa.gov/luvoir/tools/
LUMOS technology gaps

- Broadband mirror coatings for \( \lambda > 100 \text{ nm} \)
  - Partial success already – work is moving in the right direction (also – ALD)
    - environmental tests and scalability

- Large format photon counting detectors (FUV and NUV)
  - Cross-strip borosilicate MCPs
  - sCMOS or CCDs

- Low scatter (holographic) aberration correcting gratings

- Microshutter Arrays for spectral multiplexing

- High groove efficiency, low scatter echelle gratings
LUMOS technology gaps

- Broadband mirror coatings for $\lambda > 100$ nm
  - Partial success already – work is moving in the right direction (also – ALD)
    - environmental tests and scalability
- Large format photon counting detectors (FUV and NUV)
  - Cross-strip borosilicate MCPs
  - sCMOS or CCDs
- Low scatter (holographic) aberration correcting gratings
- Microshutter Arrays for spectral multiplexing
- High groove efficiency, low scatter echelle gratings

Broadband advanced coatings, large format detectors, and space-qualified MSAs all being developed and flight tested as part of NASA-supported Sounding Rocket missions, APRA programs, and Roman Technology Fellowships

(Pis – France, Green, McCandliss, Siegmund, Vallerga, Nikzad, Quijada, Fleming, and others)
Summary
LUVOIR has multiple primary science goals

① Habitable exoplanets & biosignatures
② Broad range of general astrophysics and Solar System observations

LUMOS meets the science requirements for COR and EXO

--Imaging and spectroscopy over ~4 arcmin², 100-400nm
--Peak A_{eff} > 10^5 cm² in FUV and > 1.8 x 10^5 cm² in NUV
--Imaging Spectroscopy θ < 30mas at \( R = 30,000-65,000 \) across band
--BEF ≈ few x 10^{-21} erg cm^{-2} s^{-1} Å^{-1} in LowLow Mode

Wide range of capabilities to enable decades of future investigations and unexpected discoveries