The Thirty Meter Telescope

Extremely Big Eyes on the Early Universe

Rome, Sep. 09, 2019

Christophe Dumas
Observatory Scientist & Head of Operations
TMT International Observatory, LLC
Plan

- Introduction to TMT project
  - Partnership
  - Telescope design
  - Construction site(s)
- Science and instruments
- Status of systems design and construction
TMT Partnership: Timeline

- Thirty-Meter-Telescope (TMT) = Merging of 3 earlier projects. Current cost ~1,500 M$
  - CELT: California Extremely Large Telescope (30m diameter). Caltech and Univ. California
  - VLOT: Very Large Optical Telescope (20m diameter). Canadian Universities for Research in Astronomy (ACURA)
  - GSMT: Giant Segmented Mirror Telescope (30m). National Optical Astronomical Observatory (NOAO) & Gemini Observatory
- 2003: Foundation of TMT Observatory Corporation (Caltech, UC, ACURA)
- 2008: NAOJ joins
- 2009: Funding provided by G. & B. Moore Foundation
- 2014: Chinese & Indian partners officially join
- 2016: TMT becomes TIO: TMT International Observatory
International Partnership and construction site(s)

La Palma Island (alternate site)

Hawai’i Island (prime site)

Univ. of California & Caltech

CHINA

JAPAN

INDIA

CANADA
US-ELT Program

2 telescopes, 2 hemispheres, 1 system
All-sky coverage
Broad instrument suite
US-led Key Science Programs

U.S. EXTREMELY LARGE TELESCOPE PROGRAM
Under Development by
NOAO, TIO, GMTO

NSF's National Optical Astronomy Observatory (NOAO)
Giant Magellan Telescope Organization (GMTO)
Thirty Meter Telescope International Observatory (TIO)

Overlap area ➔ Airmass < 2 for 2 hours or more
AURA has been an Associate Member of the TMT on behalf of the US national community.

Through a cooperative agreement with the NSF, a model for potential US partnership has been developed:

- International Science Development Teams
- Detailed TMT Science case
- Organization of TMT science forums
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TMT in a nutshell

- Wide-field, Alt-Az Ritchey-Chretien telescope
- 30 meter diameter primary mirror (492 hexagonal segments, 1.44m across corners)
- Passive secondary mirror
- Flat tertiary mirror beam light to Nasmyth focus
- **Up to 8 instruments** on Nasmyth
- **First-light AO system (NFIRAOS):**
  - Laser Guide Star Facility (LGSF) Multi-Conjugate-AO (MCAO)
  - Diffraction-limit at J, H, and K bands, can feed 3 instruments.
TMT: Optical design & instruments

Optical design: Ritchey-Chrétien

M1: 30m (hyperboloidal f/1)

M2: 3.1m (convex hyperboloidal)

M3: 2.5m x 3.5m (flat)

f/15 final focal ratio & 20 arcmin FoV (2.62m Ø)
**Expected boost in performance**

- **SENSITIVITY:** $S \sim D^2$
  - ~10 times the collecting area of Keck, or ~150 times that of the HST
  - For AO on point sources: $S \sim D^4$, i.e. ~200 times better than current VLTs

- **ANGULAR RESOLUTION:**
  - 12 times better HST
TMT operations model

- Similar to VLT operations (phases 1, 2, 3)
- Operations staffing level ~120 persons
- Visitor and service modes + ToOs + eavesdropping + DDTs
- Adaptive scheduling implemented to match program requirements with ambient conditions
- Execution made from science operations headquarters (Hilo or Tenerife) with possibility to eavesdrop from remote locations across TMT partnership
- TMT data will be pushed towards archive (18-month proprietary period)
Construction Site
# Thirty Meter Telescope

## Site Locations

### Maunakea Observatory

<table>
<thead>
<tr>
<th>Site characteristics</th>
<th>MKO (USA)</th>
<th>ORM (Spain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude of site (m)</td>
<td>4050</td>
<td>2250</td>
</tr>
<tr>
<td>Fraction of yearly usable time (%)</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>Seeing at 60m above ground (arcsecond)</td>
<td>0.50</td>
<td>0.55</td>
</tr>
<tr>
<td>Isoplanatic angle (arcsecond)</td>
<td>2.55</td>
<td>2.33</td>
</tr>
<tr>
<td>Atmospheric coherence time (ms)</td>
<td>7.3</td>
<td>6.0</td>
</tr>
<tr>
<td>Precipitable Water Vapor (% of time &lt; 2mm)</td>
<td>54</td>
<td>20</td>
</tr>
<tr>
<td>Mean nighttime temperature (°C)</td>
<td>2.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Extinction (V mag/airmass)</td>
<td>0.111</td>
<td>0.137</td>
</tr>
<tr>
<td>Ground dust concentration (µg/m³)</td>
<td>0.815</td>
<td>1.006</td>
</tr>
</tbody>
</table>

### Observatorio del Roque de Los Muchachos

[Image of Maunakea Observatory]

[Image of Observatorio del Roque de Los Muchachos]

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Significant funding provided by the Gordon and Betty Moore Foundation.
Maunakea & TMT

- **July 2009**: TMT Board of Directors select Mauna Kea as the preferred site for the Thirty-Meter Telescope
- **2015**: Multiple attempts to start construction fail due to opponents’ road blockades
- **December 2015**: Hawaii Supreme Court mandates rehearing of construction permit due to flaw in the application process
- **2016-2019**: Going through contested case hearings again & reprocessing permit request
- **Summer 2019**: Still cannot access summit
Maunakea & TMT

July 2009:
The TMT Board of Directors select Mauna Kea as the preferred site for the Thirty-Meter Telescope.

2015:
Multiple attempts to start construction fail due to opponents' road blockades.

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Hawaii Supreme Court mandates rehearing of construction permit due to flaw in the application process.

2016-2019:
Going through contested case hearings again & reprocessing permit request.

Summer 2019:
Still cannot access summit.
Timeline of construction permit process

Maunakea (10-year process):
- **2009**: Maunakea selected for TMT
- **2016-2017**: 1.5 years long contested case
- **Sep. 2017**: BLNR approves the Construction District Use Permit
- **2018**: Apparent stronger and more “open” local support than in 2015 ... *calm before the storm*
  - Appeal #1 (Feb. 2017): No need for another contested case about the sublease between UH and TMT
- **2019**: Re-start blocked again by TMT opponents

La Palma (2.5-year process):
- **2016**: La Palma becomes TMT’s alternate site
- **2017**: Hosting Agreement MOU signed between TIO and IAC
- **2017**: Collaboration agreement signed between TIO, IAC, La Palma government & local municipality
- **Nov. 2018**: Authorities validated our Environmental Impact Study.
- **Summer 2019**: Ecologists contest chronogram of admin process wrt land concession (one admin step to be redone)
- **September 2019**: Will be in a position to formally request building permit by end of September 2019
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Sites:

Maunakea:
- Construction to start soon
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**Current timeline**

- **As of now:** In Hawaii, Maunakea cannot be accessed. Access to La Palma is one admin step away.
- **2019 (2020):** Construction starts in Hawaii (or La Palma)
- **2021-2025:** Enclosure base & assembly
  - End 2026: End construction of all summit buildings
- **2025-2027:** Telescope structure integration
- **2027-2030:** AIV, commissioning (partial first-light opportunities)
- **2030:** “Full first-light”
Science instruments
TMT Science & instrumentation

- Contemporary Science
  - Fundamental physics & cosmology
  - Early Universe & galaxy formation
  - Super massive black-holes
  - Nearby-galaxies & Milky-way
  - Star formation & exoplanets
  - Time-domain science
  - Solar-system

- Synergies with other observatories
  - JWST, EUCLID, WFIRST
  - ALMA, LSST, SKA

- Future opportunities
  - 30 m aperture opens new exploration parameter space
    - Gravitational wave’s optical transients
    - Multi-wavelengths study programs
<table>
<thead>
<tr>
<th>Theme</th>
<th>Science Area</th>
<th>Observations</th>
<th>Requirements</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology and fundamental physics</td>
<td>• Dark matter structure on large and small scales</td>
<td>• Proper motions in dwarf galaxies</td>
<td>• $\Delta \lambda = 0.31–0.62, 2–2.4\mu$m</td>
<td>SLW/FOS</td>
</tr>
<tr>
<td></td>
<td>• Dark energy/matter effect on cosmic expansion rate</td>
<td>• Wide-field optical spectroscopy of R = 24.5 galaxies</td>
<td>• Seeing-limited FOV &gt; 10'</td>
<td>MCAO/IRIS imager</td>
</tr>
<tr>
<td></td>
<td>• Neutron star equation of state and testing gravity</td>
<td>• Transient events lasting &gt; 30 days</td>
<td>• 4-mas/pixel K band imaging FOV &gt; 30&quot;</td>
<td>MCAO/MODHiS imager</td>
</tr>
<tr>
<td></td>
<td>• Variations of physical constants over cosmic time</td>
<td>• High resolution spectroscopy of QSOs and gamma-ray bursts (GRBs)</td>
<td>• R = 1,000–50,000</td>
<td>SL/HROS</td>
</tr>
<tr>
<td>The early Universe</td>
<td>• Metal-free star formation in first light objects</td>
<td>• Faint object multiplexed, spatially-resolved spectroscopy</td>
<td>• Very efficient acquisition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Gravitationally lensed first light objects</td>
<td>• High-resolution NIR spectroscopy</td>
<td>• 0.05-mas astrometry stable over 10 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Early galaxies and re-ionization</td>
<td>• Diffraction-limited NIR imaging</td>
<td>• MCAO/IRIS IFS, MCAO/IRIS imager</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Structure and neutral fraction of z &gt; 7 IGM</td>
<td>• Optical/NIR multiplexed and Seeing-/Diffraction-limited spatially-resolved spectroscopy of distant galaxies, AGNs and R ~ 27 high redshift objects</td>
<td>• Exposure times &gt; 16 ks</td>
<td>MCAO/MODHiS, MOAO/IRMOS</td>
</tr>
<tr>
<td>Galaxy formation and the IGM</td>
<td>• Connecting the distributions of stars and dark matter</td>
<td>• Optical/NIR multiplexed and Seeing-/Diffraction-limited spatially-resolved spectroscopy of distant galaxies, AGNs and R ~ 27 high redshift objects</td>
<td>• $\Delta \lambda = 0.31–2.5\mu$m</td>
<td>SLW/FOS</td>
</tr>
<tr>
<td></td>
<td>• Baryon Cycle at peak galaxy formation epoch</td>
<td>• Optical/NIR multiplexed and Seeing-/Diffraction-limited spatially-resolved spectroscopy of distant galaxies, AGNs and R ~ 27 high redshift objects</td>
<td>• R = 3,000–5,000, 50,000</td>
<td>MCAO/IRIS IFS</td>
</tr>
<tr>
<td></td>
<td>• Evolution of velocity, star formation rates, extinction and metallicity maps of z = 5.5 to &lt; 1.5 galaxies</td>
<td>• Very efficient acquisition</td>
<td>• High multiplexing (goal &gt; 100)</td>
<td>SL/HROS</td>
</tr>
<tr>
<td></td>
<td>• IGM/CGM properties on scales &lt; 300-kpc</td>
<td>• High multiplexing (goal &gt; 100)</td>
<td>• MOAO/IRMOS</td>
<td></td>
</tr>
</tbody>
</table>

- 30 m aperture opens new exploration parameter space
- Gravitational wave’s optical transients
- Multi-wavelengths study programs
# TMT envisioned instruments suite

<table>
<thead>
<tr>
<th>Instrument and Description</th>
<th>$\lambda$ Range ((\mu)m)</th>
<th>Spectral Resolution</th>
<th>Modes</th>
<th>Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IRIS/Diffraction-Limited NIR Imager and IFS</strong></td>
<td>0.84–2.4</td>
<td>Y, Z, J, H, K, wide and narrow filters, 4,000–8,000 (some modes to 10,000)</td>
<td>NGSAO, MCAO</td>
<td>Imager - 34&quot; x 34&quot; @ 0.004&quot;/pix IFU - 0.51&quot; x 0.51&quot; @ 0.004&quot;/pix to 2.25&quot; x 4.4&quot; @ 0.050&quot;/pix</td>
</tr>
<tr>
<td><strong>WFOS/Wide-Field Optical Spectrometer</strong></td>
<td>0.31–1.0</td>
<td>1,500 to 5,000 0.75&quot; slits, 10,000 0.25&quot; slits</td>
<td>SL, GLAO*</td>
<td>25.5 (8.3 x 3)-arcmin$^2$, 500&quot; total slit length (about 58 targets with 8&quot; slits, 0.5&quot; gaps), 0.05&quot;/pixel</td>
</tr>
<tr>
<td><strong>MODHIS/Multi-Object Diffraction-Limited High-Resolution Infrared Spectrograph</strong></td>
<td>0.95–2.5</td>
<td>110,000 - 180,000 &lt; 10 cm/s (goal 2 cm/s)</td>
<td>NGSAO</td>
<td>4 (goal &gt;5) 0.1&quot;x 0.1&quot; collectors, @ 0.02&quot; spatial sampling, 10&quot; diameter field of regard with coronagraph</td>
</tr>
<tr>
<td><strong>PSI/Planetary System Instrument</strong></td>
<td>1–5</td>
<td>IFS ~ 5,000, Imager &lt; 100</td>
<td>ExAO</td>
<td>Approximately 1&quot; outer working angle, Approximately 10 mas inner working angle</td>
</tr>
<tr>
<td><strong>MICH/Trans-IR Imager, IFU and Spectrometer</strong></td>
<td>7.3–13.8</td>
<td>Imager &lt; 100, IFS 600–1,000, Spectrometer 120,000</td>
<td>MIRAO</td>
<td>Imager: 24&quot;x 24&quot; @ 0.011&quot;/pix, IFU: 5&quot;x 2&quot; Coronagraph</td>
</tr>
<tr>
<td><strong>HROS/High-Resolution Optical Spectrograph</strong></td>
<td>0.31–1</td>
<td>50,000–2 90,000</td>
<td>SL, GLAO</td>
<td>5&quot; total slit length</td>
</tr>
<tr>
<td><strong>IRMOS/IR Multi-Object Spectrograph</strong></td>
<td>0.8–2.5</td>
<td>2,000–10,000</td>
<td>MOAO</td>
<td>&gt; ten 3&quot; IFUs over &gt; 5&quot; diameter field</td>
</tr>
</tbody>
</table>
TMT instruments
First-light discovery space

First-light instruments capabilities

- **MODHIS**
  - (IGM $z>7$, chemistry of star formation, low-mass stars RV, exoplanet atmospheres, stellar abundances, SN/Gamma-Ray burst)

- **WFOS**
  - (IGM structure, dark matter, galaxy chemistry $z>1.5$, SN/gamma-ray burst)

- **IRIS**
  - (AGN, SMBH, high-z galaxies, dark matter, dark energy, exoplanets, star formation, stellar population)
# InfraRed Imager and Spectrograph (IRIS)

**Main Characteristics**

<table>
<thead>
<tr>
<th><strong>Wavelength coverage</strong></th>
<th>0.84-2.4(\mu)m</th>
</tr>
</thead>
</table>

**Adaptive optics capabilities**

- NIRFRAOS/LGS
- On-instrument wavefront sensors (tip-tilt, focus, distortion)

**Wavefront error**

< 40nm (fine platescales)

**Imaging:**

- Imaging FoV: 34”x34” (2x2 H4RG-10 arrays)

**Filters**

- PSSN: Broad + selection of NB (tbd)
- (SN~100, 1hr) - H: 26.2, K: 25.6

**Spectroscopy:**

- Integral-field-spectrograph (IFS) FoV: 0.5”, 1.1”, 1.7”, 3.3” (H4RG-15)

- Resolution Sensitivity: 4000, 8000 (SN~10, 15min) - H: 25.8, K: 24.2

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**PI:** J. Larkin (UCLA)  
**PM, co-PI:** E. Chisholm (TMT)  
**PS:** S. Wright (UCSD)
### Main Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength coverage</td>
<td>0.31-1.0µm (~700nm continuous coverage @R=1500)</td>
</tr>
<tr>
<td>Seeing-limited</td>
<td>(GLAO with deformable M2)</td>
</tr>
<tr>
<td>FoV</td>
<td>~25 arcmin² (8.3’x3’)</td>
</tr>
<tr>
<td>Resolution</td>
<td>1,500-15,000</td>
</tr>
<tr>
<td>MOS</td>
<td>500” total slit length</td>
</tr>
</tbody>
</table>

- Slit-based and fiber-based systems were initially considered.
- Slit-based architecture selected in October 2018.
- Conceptual Design phase begins.
Multi-Object Diffraction-limited High-resolution Infrared Spectrograph (MODHIS)

Main Characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength coverage</td>
<td>0.95-2.5μm</td>
</tr>
<tr>
<td>FIU fed by NFIRAOS 1st light AO system</td>
<td></td>
</tr>
<tr>
<td>Patrol field</td>
<td>2”-5” diffraction limited</td>
</tr>
<tr>
<td>Resolution</td>
<td>100,000 and 30 cm/s</td>
</tr>
<tr>
<td>MOS</td>
<td>Up to 25 objects with 0.1”IFU@0.02”sampling</td>
</tr>
<tr>
<td>Throughput</td>
<td>&gt;10%</td>
</tr>
</tbody>
</table>

Pathfinder fiber injection unit for KPIC
TMT instruments
First-light & next-generation

First-light + next-generation instruments capabilities

- **HROS**
  - (IGM z<6, ISM/stellar abundances, kinematics, exoplanets RV, cosmology)

- **MODHIS**
  - (IGM z>7, chemistry of star formation, low-mass stars RV, exoplanet atmospheres, stellar abundances, SN/Gamma-Ray burst)

- **PSI-b**
  - (IGM structure, dark matter, galaxy chemistry z>1.5, SN/gamma-ray burst)

- **IRMOS**
  - (early universe, JWST follow-up)

- **IRIS**
  - (AGN, SMBH, high-z galaxies, dark matter, dark energy, exoplanets, star formation, stellar population)

- **PSI-r**
  - (star formation, disks, exoplanets, solar system, AGN)

- **PSI-mIR**
  - (star formation, disks, exoplanets, solar system, AGN)

- **WFOS**
  - (exoplanets, star formation, AGN, solar system)

- **b-MICH**
  - (AGN, SMBH, high-z galaxies, dark matter, dark energy, exoplanets, star formation, stellar population)
TMT instruments
First-light & next-generation

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- **WFOS**
  - (exoplanets, star formation, AGN, solar system)

- **PSI-b**
  - (early universe, JWST follow-up)

- **PSI-r**
  - (star formation, disks, exoplanets, solar system, AGN)

- **PSI-PAIR**
  - (dedicated AO system)

- **b-MICH**
  - (IGM z>7, chemistry of star formation, low-mass stars RV, exoplanet atmospheres, stellar abundances, SN/Gamma-Ray burst)

- **NFIRAOS**
TMT instruments
Spatial resolution

First-light + next-generation instruments capabilities

Spectral resolution

Spatial resolution (mas)

MODHIS

IRMOS

IRIS

PFI

MICHI

ExAO, SAO, MCAO, MOAO, LTAO

HROS

WFOS

WFOS

Seeing limited
Possible timeline of instrument deployment

1st light and “next-generation”

Full 1st light
WFOS
IRIS
Adaptive Optics
MODHIS

Deployment of
HROS, PSI (-blue), IRMOS

Deployment of future instrument
capabilities (still tbd)

Possible deployment of PSI (-red) & MICHI

Start of construction
2020
2030
2040
2050

TMT in operations until 2080+

Recommendation: The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community. (Chapter 4)

Recommendation: NASA should implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions. (Chapter 5)

From “Astrobiology strategy to search for life in the universe”, 2018, National Academy Press
Quick update on Project/system advancement
All critical systems are at an advanced state of design, while some are already in production.
Snapshot of systems design/production

M3 prototype

Segment Support Assembly

Main structural node (MELCO confidential)

NFIRAOS, TMT AO system

Actuators components and edge sensors (NASA/JPL: design, India: production)
82 types of segments (different curvature) duplicated over 6 sectors
- 7 mirror segments of each type must be produced (include 1 spare)

Japan: 174
India: 86
China: 86
CIT/UC: 146 + 82

Total: 492 segments
Spares: 82 segments
Gran Total: 574 segments
Polishing activities starting across partnership
... while waiting for real construction images

Thank you!
Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA), the U.S. National Science Foundation and the National Institutes of Natural Sciences of Japan.