A Unique Time and a Unique Place

Exploring the hidden universe

Gordon K. Squires
Caltech/IPAC
What, how, when, where and ... why?
SoCal - A Golden Age

- Spitzer
- Herschel
- GALEX
- WISE
- Planck
- Kepler
- TMT
- Keck
- Palomar
- (CSO, CARMA, NuStar)
IPAC @ Caltech - 25 years

- Science Centers
- Data processing
- Data analysis tools
- Pipelines
- Archives
- Tools
- Communications
  - public affairs/media relations
  - “classic” E/PO
A personal age of wonder
In the beginning...  Saturn - Galileo (1610)
Saturn - Huygens (1647)

Systema Saturnium.

Cujus phæceos vera proinde forma, secundum ea quæ supra circa annulum definivimus, ejsimodi erit quæ hic delineata cernitur, majori ellipsis diametro ad minorem sè habente sè ut s ad 2.
Saturn - Keck Telescope (2005)
Saturn - NASA/Cassini (2007)
Saturn - NASA/Spitzer (2009)
Currently in-flight...
Wide-field Infrared Survey Explorer (WISE): launched 2009 December 14 at 6:09am PST
Approximately 1 yr mission; all-sky infrared survey
Kepler: “A Search for Habitable Planets” - launched March 6, 2009

Expected mission duration - 3.5 years, or more
**Herschel/Planck**: “Exploring the Cold Universe/Echoes of the Big Bang” - launched May 14, 2009

**Herschel**: expected mission duration - 3 years, or more
Expected mission duration:
15 months to 2.5 years
Galaxy Evolution Explorer: “Galaxies across 10 billion years of cosmic history” - launched April 28, 2003
Originally a 29 month mission; still in flight 8 years later; no consumables
**GALEX: Fast Facts**

- 50 cm Ritchey-Chretien telescope
- high throughput
- large field of view (1.3 deg)
- four different optical paths (two UV simultaneous channels, with imagery and slitless spectroscopy modes)
- weighs only 280 kilograms (a little over 617 pounds)
- 2 meters (6 feet 6 inches) tall and, with solar panels unfurled, it is 2.8 meters (9 feet) wide
Originally a 2.5 year mission; still in-flight 8+ years later; continue until 2016
Spitzer: fast facts

- Launch Date: 25 August 2003
- Launch Vehicle/Site: Delta 7920H ELV / Cape Canaveral, Florida
- Orbit: Earth-trailing, Heliocentric
- Wavelength Coverage: 3 - 180 microns
- Telescope: 85 cm diameter (33.5 Inches), f/12 lightweight Beryllium, cooled to less than 5.5 K
- Diffraction Limit: 6.5 microns
- Imaging / Photometry: 3-180 microns
- Spectroscopy: 5-40 microns
- Spectrophotometry: 50-100 microns
- Planetary Tracking: 1 arcsec / sec
- Cryogen / Volume: Liquid Helium / 360 liters (95 Gallons)
- Launch Mass: 950 kg (2094 lb) [Observatory: 851.5 kg, Cover: 6.0 kg, Helium: 50.4 kg, Nitrogen Propellant: 15.6 kg]
Spitzer under construction
Spitzer at the winter Olympics (2010)
The Spitzer Space Telescope in context

• Final telescope in NASA’s “Great Observatories” program

  ✴ Hubble (visible light): based at Johns Hopkins University

  ✴ Chandra (X-ray): based at Harvard

  ✴ Compton (gamma-ray): based at University of California - Berkeley

  ✴ Spitzer (infrared): based at Caltech

• Completing our understanding of the multiwavelength universe
Caltech/IPAC Contributions

- Spitzer Space Telescope science operations and science center
- GALEX science operations and science center
- NASA Herschel Science Center
- U.S. Planck Data Center
- Kepler data analysis
- WISE data center
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• Spitzer Space Telescope science operations and science center

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Where next?
NASA/JPL: Mars Science Laboratory
Launch Nov. 25, 2011
NASA/JPL: Mars Science Laboratory
Launch Nov. 25, 2011
What have we learned?
Our solar system
WISE: first known Earth Trojan asteroid
Herschel: comet Hartley 2 possesses a ratio of "heavy water" to light, or normal water that matches what’s found in Earth’s oceans.
A Near-Earth Asteroid Census

Each image represents 100 objects

- Known Asteroids
  - New Predicted Total (WISE)
  - Old Predicted Total (pre-WISE)

- > 1000 m
- 500–1000 m
- 300–500 m
- 100–300 m
- < 100 m
Determining Asteroid Sizes

Visible Light
- Brightness alone does not correspond to size

Infrared Light
- Brightness corresponds to size

High Albedo “Chalk”
- Low Albedo “Charcoal”
Finding Dark Asteroids

High Albedo “Chalk”

Visible Light

Low Albedo “Charcoal”

Hard to detect dark objects

Infrared Light

Easy to detect dark objects

High Albedo “Chalk”

Low Albedo “Charcoal”
Where do planets form?
Spitzer: Planets are everywhere! Around brown dwarfs, “normal” stars, hypergiants and neutron stars
Spitzer: planets around “planets”
0-3 AU
DISK AROUND BOTH STARS

3-50 AU
NO OBSERVED DISK

50-500 AU
DISK AROUND SINGLE STAR

(1 AU = distance between Earth and Sun)
The nature of planets
Spitzer: First detection of light from a planet outside our solar system

Planetary Eclipses  Spitzer Space Telescope • IRAC • MIPS

NASA / JPL-Caltech / D. Charbonneau (Harvard-Smithsonian CfA)
D. Deming (Goddard Space Flight Center)  ssc2005-09a
Spitzer: viewing distant planets
Spitzer: viewing distant planets
Spitzer: first weather map of a world 64 light-years away. 6000 mph winds!

Spitzer: hottest planet (3,700 F) and “blacker-than-black”
Enough water vapor to fill the oceans on Earth five times in the collapsing nest of a forming star system.

Large amounts of simple organic gases and water vapor in a possible planet-forming region.
Kepler: hundreds of new planets
1235 planet candidates
Kepler 16b: “Tatooine”
How do stars form?
Spitzer:

“Triggered” star formation
Spitzer: peering into stellar natal cocoons

Black Widow Nebula

Spitzer Space Telescope • IRAC

Visible (DSS)

NASA / JPL-Caltech / E. Churchwell (University of Wisconsin-Madison) and the GLIMPSE team
Herschel: peering into cold stellar natal cocoons
GALEX: distribution of stellar masses ("initial mass function")
The life of stars
GALEX: a star with a 13,000 light year “tail” - Mira
The death of stars
Spitzer: the death of stars, and the future of our solar system
GALEX: Watching a star fall into a black hole

Tidal Disruption of a Star by a Supermassive Black Hole

(Artist Concept)
Our galaxy
Spitzer: A 800,000 image panorama of our Milky Way

The Infrared Milky Way: GLIMPSE/MIPSGAL

Spitzer Space Telescope • IRAC • MIPS

NASA / JPL-Caltech / E. Churchwell (Univ. of Wisconsin), GLIMPSE Team & S. Carey (SSC-Caltech), MIPSGAL Team ssc2008-11a
Spitzer: Revolutionizing our understanding of the structure of our own galaxy
Herschel: \( O_2 \)
The extragalactic universe
Spitzer: Finding a “galaxy on fire”

“Cigar” Galaxy M82

NASA / JPL-Caltech / C. Engelbracht [Steward Observatory] and the SINGS team

Spitzer Space Telescope • IRAC

ssc2006-09a
GALEX: revealing the size of galaxies

Extended Disk of Galaxy M83
Buckyballs in Spaaaaaace......! Spitzer: SMC, Tc 1
Planck: all sky microwave background survey
Caltech is a premiere institution for space-based astronomy
Currently in-flight: 5 telescopes with coverage across the spectrum; number 6 was WISE, shutdown (operational)
Major scientific advances from the scale of our solar system to the Universe as a whole
Telescopes routinely exceeding design specifications
Revealing the Hidden Universe

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- Currently in-flight: 5 telescopes with coverage across the spectrum; number 6 was WISE, shutdown (operational)
- Major scientific advances from the scale of our solar system to the Universe as a whole
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Thirty Meter Telescope (TMT)

astronomy’s next-generation observatory
Fact facts

- 30m primary
  - 492 segments
- 3 first light instruments
  - IRIS: Infrared Imaging Spectrometer
  - WFOS: Wide Field Optical Spectrometer
  - IRMS: Infrared Multislit Spectrometer
- International Partnership
  - Caltech, UC, ACURA, NAOJ, NAOC, DSTI
  - NSF role clarified
- $1.2B 2011 dollars
  - $350M already raised
  - in-kind valued
- Mauna Kea
- 5 laser guidestar AO
- Construction paced by funding; operations ~2020?
Mauna Kea
4210m

Summit ridge site

13 North Site
TMT on Mauna Kea
TMT on Mauna Kea

Hawaii EIS approved!

Hawaii CDUP approved!
TMT and Keck I & II

Image courtesy of M3 Engineering
5 Meter
Hale 200-inch Mirror

10 Meter
Keck Mirror

30 Meter
TMT Mirror
Early light instruments are expected to be available at the start of TMT science operations. This category includes the following instruments:

- Wide-Field Optical Spectrometer (WFOS)
- InfraRed Imaging Spectrometer (IRIS)
- InfraRed Multi-slit Spectrometer (IRMS)

Future instruments are expected to be commissioned with the first decade of TMT operations. They include:

- Planet Formation Instrument (PFI)
- High-Resolution Optical Spectrometer (HROS)
- Mid-InfraRed Echelle Spectrometer (MIRES)
- InfraRed Multi-Object Spectrometer (IRMOS)
- Near-InfraRed Echelle Spectrometer (NIRES)
# TMT Planned Instrument Suite

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<th>Instrument</th>
<th>$\lambda$ (µm)</th>
<th>Field of view/Slit length</th>
<th>Spectral resolution</th>
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| InfraRed Imager and Spectrometer (IRIS)  | 0.8 – 2.5      | <3’’ IFU >15’’ imaging    | > 3500              | • Assembly of galaxies at high z  
• Black holes/AGNs/Galactic Center  
• Resolved stellar populations in crowded fields                                |
|                                          | 0.6 – 5 (goal) |                           | 5-100 (imaging)     |                                                                              |
| Wide-field Optical spectrometer and imager (WFOS) | 0.31 – 1.0     | >40 arcmin$^2$ >100 arcmin$^2$ (goal) Slit length >500’’ | 1000-5000@0.75’’ slit >7500 @0.75’’ (goal) | • IGM structure and composition at 2 < z < 6  
• Stellar populations, chemistry and energetics of z > 1.5 galaxies                |
| InfraRed Multislit Spectrometer (IRMS)   | 0.95 – 2.45    | 2 arcmin field, up to 120’’ total slit length with 46 deployable slits | R=4660 @ 0.16 arcsec slit | • Early Light  
• Epoch of peak galaxy building  
• JWST follow-ups                                                             |
| Deployable, multi-IFU, near-IR spectrometer (IRMOS) | 0.8 – 2.5      | 3’’ IFUs over >5’ diameter field | 2000-10000         | • Early Light  
•Epoch of peak galaxy building  
• JWST follow-ups                                                              |
| Mid-IR AO-fed Echelle spectrometer (MIRES) | 8 – 18         | 3’’ slit length 10’’ imaging | 5000-100000       | • Origin of stellar masses  
• Accretion and outflows around protostars  
• Evolution of gas in protoplanetary disks                                      |
|                                          | 4.5 – 28 (goal) |                           |                     |                                                                              |
| Planet Formation Instrument (PFI)        | 1 – 2.5        | 1’’ outer working angle, 0’’.05 inner working angle | R≤100               | • 10$^6$ contrast ratio (10$^9$ goal)  
• Direct detection and spectroscopic characterization of exoplanets              |
|                                          | 1 – 5 (goal)   |                           |                     |                                                                              |
| Near-IR AO-fed echelle spectrometer (NIRES) | 1 - 5          | 2’’ slit length           | 20000-100000       | • IGM at z > 7, gamma-ray bursts  
• Local Group abundances  
• Abundances, chemistry and kinematics of stars and planet-forming disks  
• Doppler detection of terrestrial planets around low-mass stars                   |
| High-Resolution Optical Spectrometer (HROS) | 0.31 – 1.1     | 5’’ slit length           | 50000              | • Doppler searches for exoplanets  
• Stellar abundance studies in Local Group  
• ISM abundance/kinematics  
• IGM characteristics to z~6                                                        |
| “Wide”-field AO imager (WIRC)            | 0.8 – 5.0      | 30’’ imaging field        | 5-100              | • Precision astrometry (e.g., Galactic Center)  
• Resolved stellar populations out to 10 Mpc                                           |
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<td>10⁶ contrast ratio (10⁹ goal)</td>
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<td>0”.05 inner working angle</td>
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<td>&gt; 3500&lt;br&gt;5-100 (imaging)</td>
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<td>5000&lt;br&gt;5000@0.75” slit&lt;br&gt;7500 @0.75”&lt;br&gt;(goal)</td>
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</tr>
<tr>
<td>Instrument</td>
<td>λ (µm)</td>
<td>Field of view/Slit length</td>
<td>Spectral resolution</td>
<td>Science Cases</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-----------------</td>
<td>---------------------------</td>
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<td>-------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| InfraRed Imager and Spectrometer (IRIS)        | 0.8 – 2.5, 0.6 – 5 (goal) | <3” IFU, 15”imaging       | > 3500, 5-100 (imaging) | • Assembly of galaxies at high z  
• Black holes/AGNs/Galactic Center  
• Resolved stellar populations in crowded fields |
| Wide-field Optical spectrometer and imager (WFOS) | 0.31 – 1.0      | >40 arcmin², >100 arcmin² (goal) | 1000-5000@0.75” slit >7500@0.75” (goal) | • IGM structure and composition at 2 < z < 6  
• Stellar populations, chemistry and energetics of z > 1.5 galaxies |
| InfraRed Multislit Spectrometer (IRMS)         | 0.95 – 2.5      | 3” IFUs over >5’ diameter field | 2000-10000          | • Early Light  
• Epoch of peak galaxy building  
• JWST follow-ups |
| Deployable, multi-IFU, near-IR spectrometer (IRMOS) | 0.8 – 2.5 | 3” slits length, 10” imaging | 5000-100000         | • Origin of stellar masses  
• Accretion and outflows around protostars  
• Evolution of gas in protoplanetary disks |
| Mid-IR AO-fed Echelle spectrometer (MIRES)      | 8 – 18, 4.5 – 28 (goal) | 3” slit length            | 5000-100000         | • 10⁻⁵ contrast ratio (10⁻⁶ goal)  
• Direct detection and spectroscopic characterization of exoplanets |
| Planet Formation Instrument (PFI)               | 1 – 2.5, 1 – 5 (goal) | Outer working angle, 0’’.05 inner working angle | R≤100               | • IGM at z > 7, gamma-ray bursts  
• Local Group abundances  
• Abundances, chemistry and kinematics of stars and planet-forming disks  
• Doppler detection of terrestrial planets around low-mass stars |
| Near-IR AO-fed echelle spectrometer (NIRES)     | 1 - 5           | 2” slit length            | 20000-100000        | • Doppler searches for exoplanets  
• Stellar abundance studies in Local Group  
• ISM abundance/kinematics  
• IGM characteristics to z~6  

“Wide”-field AO imager (WIRC) | 0.8 – 5.0 | 30” imaging field | 5-100 | • Precision astrometry (e.g., Galactic Center)  
• Resolved stellar populations out to 10 Mpc |
<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\lambda$ (μm)</th>
<th>Field of view/Slit length</th>
<th>Spectral resolution</th>
<th>Science Cases</th>
</tr>
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</table>
| InfraRed Imager and Spectrometer (IRIS)       | 0.8 – 2.5      | <3” IFU                                   | > 3500              | • Assembly of galaxies at high z  
• Black holes/AGNs/Galactic Center  
• Resolved stellar populations in crowded fields |
|                                               | 0.6 – 5 (goal) | >15”imaging                               | 5-100 (imaging)     |                                                                               |
| Wide-field Optical spectrometer and imager (WFOS) | 0.31 – 1.0     | >40 arcmin$^2$                             | 1000-5000@0.75” slit | • IGM structure and composition at $2 < z < 6$  
• Stellar populations, chemistry and energetics of $z > 1.5$ galaxies |
|                                               |                | >100 arcmin$^2$ (goal)                    | >7500 @0.75” (goal) |                                                                               |
| InfraRed Multislit Spectrometer (IRMS)        | 0.95 – 2.45    | 2 arcmin field, up to 120’ total slit length with 46 deployable slits | R=4660 @ 0.16 arcsec slit | • Early Light  
• Epoch of peak galaxy building  
• JWST follow-ups |
| Deployable, multi-IR-U, near-IR spectrometer (IRMOS) | 0.8 – 2.5      | 3” IFUs over >5’ diameter field           | 2000-10000          | • Early Light  
• Epoch of peak galaxy building  
• JWST follow-ups |
| Mid-IR AO-fed Echelle spectrometer (MIRES)    | 8 – 18         | 3” slit length                            | 5000-100000         | • Origin of stellar masses  
• Accretion and outflows around protostars  
• Evolution of gas in protoplanetary disks |
|                                               | 4.5 – 28 (goal)| 10’’ imagering                            |                     |                                                                               |
| Planet Formation Instrument (PFI)             | 1 – 2.5        | 1” outer working angle, 0”.05 inner working angle | R≤100               | • $10^5$ contrast ratio ($10^5$ goal)  
• Direct detection and spectroscopic characterization of exoplanets |
|                                               | 1 – 5 (goal)   |                                            |                     |                                                                               |
| Near-IR AO-fed echelle spectrometer (NIRES)   | 1 - 5          | 2” slit length                            | 20000-100000        | • IGM at $z > 7$, gamma-ray bursts  
• Local Group abundances  
• Abundances, chemistry and kinematics of stars and planet-forming disks  
• Doppler detection of terrestrial planets around low-mass stars |
| High-Resolution Optical Spectrometer (HROS)   | 0.31 – 1.1     | 5” slit length                            | 50000               | • Doppler searches for exoplanets  
• Stellar abundance studies in Local Group  
• ISM abundance/kinematics  
• IGM characteristics to $z<6$ |
| “Wide”-field AO imager (WIRC)                 | 0.8 – 5.0      | 30” imaging field                         | 5-100               | • Precision astrometry (e.g., Galactic Center)  
• Resolved stellar populations out to 10 Mpc |
|                                               |                |                                            |                     |                                                                               |
Motivation for IRIS

<table>
<thead>
<tr>
<th>Scale</th>
<th>Distance</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 AU</td>
<td>36 km</td>
<td></td>
<td>(Jovian moons)</td>
</tr>
<tr>
<td>5 pc</td>
<td>0.05 AU</td>
<td></td>
<td>(Nearby stars - companions)</td>
</tr>
<tr>
<td>100 pc</td>
<td>1 AU</td>
<td></td>
<td>(Nearest star forming regions)</td>
</tr>
<tr>
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<td>(Typical Galactic Objects)</td>
</tr>
<tr>
<td>8.5 kpc</td>
<td>85 AU</td>
<td></td>
<td>(Galactic Center or Bulge)</td>
</tr>
<tr>
<td>1 Mpc</td>
<td>0.06 pc</td>
<td></td>
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</tr>
<tr>
<td>20 Mpc</td>
<td>1 pc</td>
<td></td>
<td>(Virgo Galaxy Cluster)</td>
</tr>
<tr>
<td>z = 0.5</td>
<td>0.07 kpc</td>
<td></td>
<td>Galaxies at Sun’s formation</td>
</tr>
<tr>
<td>1.0</td>
<td>0.09 kpc</td>
<td></td>
<td>(Disk evolution, drop in star formation rate)</td>
</tr>
<tr>
<td>2.5</td>
<td>0.09 kpc</td>
<td></td>
<td>(QSO epoch)</td>
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Titan with 0''.05 grid (≈ 300 km)

M31 Bulge with 0''.1 grid
## Motivation for IRIS

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<tr>
<th>Distance (AU)</th>
<th>Equivalent (km)</th>
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<tr>
<td>5</td>
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<td>10</td>
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</tr>
<tr>
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<td>0.1</td>
<td>(Typical Galactic Objects)</td>
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<td>0.7</td>
<td>(Disk evolution, drop in star formation rate)</td>
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<tr>
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</tr>
<tr>
<td>0.07</td>
<td>0.7</td>
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**Titan with 0''.05 grid (~ 300 km)**

**M31 Bulge with 0''.1 grid**
Motivation for IRIS

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Titan with 0''.05 grid (~ 300 km)

M31 Bulge with 0''.1 grid
## Motivation for IRIS

### Motivation for IRIS

**5 AU = 36 km**  
(Jovian moons)

**5 pc = 0.05 AU**  
(Nearby stars - companions)

**100 pc = 1 AU**  
(Nearest star forming regions)

**1 kpc = 10 AU**  
(Typical Galactic Objects)

**8.5 kpc = 85 AU**  
(Galactic Center or Bulge)

**1 Mpc = 0.06 pc**  
(Nearest Galaxies)

**20 Mpc = 1 pc**  
(Virgo Galaxy Cluster)

**z = 0.5 = 0.07 kpc**  
Galaxies at Sun’s formation

**1.0 = 0.09 kpc**  
(Disk evolution, drop in star formation rate)

**2.5 = 0.09 kpc**  
(QSO epoch)

**5.0 = 0.07 kpc**  
(Protogalaxies, QSOs, reionization)

---

**Titan with 0''.05 grid**  
(~ 300 km)

**M31 Bulge with 0''.1 grid**
IRIS Team

- James Larkin (UCLA), Principal Investigator
  - Overall IRIS instrument + lenslet-based IFS
  - ADC and optical design: UCSC
- Anna Moore (Caltech), co-PI
  - Sharing overall instrument responsibilities + slicer-based IFS
- Ryuji Suzuki, Masahiro Konishi, Tomonori Usuda (NAOJ)
  - Imager design
- Betsy Barton (UC Irvine), Project Scientist - Science Team:
  - Shri Kulkarni (Caltech), Jonathan Tan (U. Florida), Máté Ádámkovics, Joshua Bloom, James Graham, (UC Berkeley), Pat Côté, Tim Davidge (HIA), Shelley Wright (UC Irvine), Bruce Macintosh (LLNL), Miwa Goto (MPIA), Nobunari Kashikawa (NAOJ), Jessica Lu, Andrea Ghez, David Law, Will Clarkson (UCLA), Hajime Sugai (Kyoto)
- David Loop, Murray Fletcher, Vlad Reshetov, Jennifer Dunn (HIA)
  - On-instrument wavefront sensors
- Dae-Sik Moon (U. of Toronto): NFIRAOS Science Calibration Unit
<table>
<thead>
<tr>
<th>Requirement #</th>
<th>Description</th>
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</tr>
</thead>
<tbody>
<tr>
<td>[REQ-1-ORD-3950]</td>
<td>Wavelength Range</td>
<td>0.31 – 1.0μm</td>
</tr>
<tr>
<td>[REQ-1-ORD-3955]</td>
<td>Image quality: Imaging</td>
<td>≤ 0.2 arcsec FWHM over any 0.1μm wavelength interval (including contributions from the telescope and the ADC at z=60°)</td>
</tr>
<tr>
<td>[REQ-1-ORD-3960]</td>
<td>Image quality: Spectroscopy</td>
<td>≤ 0.2 arcsec FWHM at every wavelength</td>
</tr>
<tr>
<td>[REQ-1-ORD-3965]</td>
<td>Field of View</td>
<td>40.5 arcmin². The field need not be contiguous.</td>
</tr>
<tr>
<td>[REQ-1-ORD-3970]</td>
<td>Total Slit Length</td>
<td>≥ 500 arcseconds</td>
</tr>
<tr>
<td>[REQ-1-ORD-3975]</td>
<td>Spatial Sampling</td>
<td>&lt; 0.15 arc-sec per pixel, goal &lt; 0.1 arc-sec</td>
</tr>
<tr>
<td>[REQ-1-ORD-3980]</td>
<td>Spectral Resolution</td>
<td>R = 500-5000 for a 0.75 arc-sec slit, 150-7500 (goal)</td>
</tr>
<tr>
<td>[REQ-1-ORD-3985]</td>
<td>Throughput</td>
<td>≥ 30% from 0.31 – 1.0μm, or at least as good as that of the best existing spectrometers</td>
</tr>
<tr>
<td>[REQ-1-ORD-3990]</td>
<td>Sensitivity</td>
<td>Spectra should be photon noise limited for all exposure times &gt;60 sec. Background subtraction systematics must be negligible compared to photon noise for total exposure times as long as 100 Ksec. Nod and shuffle capability in the detectors may be desirable</td>
</tr>
<tr>
<td>[REQ-1-ORD-3995]</td>
<td>Wavelength Stability</td>
<td>Flexure at a level of less than 0.15 arc-sec at the detector is required.</td>
</tr>
</tbody>
</table>
Different WFOS designs were studied during the instrument feasibility study phase. The current design for WFOS is known as the “Multi-Object Broadband Imaging Echellette” (MOBIE) spectrometer.
InfraRed Multi-slit Spectrometer (IRMS) (aka Keck/MOSFIRE on TMT)
Partnership in-place
Path to construction clarified
Hurdles for construction almost resolved
NSF role becoming clearer
Advance telescope design, driven by science requirements
  - First-generation instruments defined
  - Priorities for second-generation instruments defined
Acknowledgments

The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. 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) and the U.S. National Science Foundation.