NASA’s IRTF in the Era of 30-m Infrared Telescopes

Michael J. Mumma
NASA Goddard Space Flight Center

Biosphere 2, Oracle, Arizona February 14, 2018
Processes affecting ices and dust in Proto-planetary Disks

The composition of disk material is extremely sensitive to initial composition, nebular processing, and nebular dynamics.
Origin of Earth’s Volatiles

- Noble gas depletions show Earth has a secondary atmosphere
- D/H is enriched in water by ~ 7 relative to nebular Hydrogen

Model 1: Volatiles outgassed during and/or after accretion
✓ Models of outgassing of chondritic material

Model 2: Exogenous delivery after Earth-Moon formation
✓ Composition of comets, meteorites, & lunar breccias.
✓ Observations of dense clouds, hot cores, & CS disks.
✓ Chemical models & lab simulations.

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IRTF in the Era of Extremely Large Telescopes

2018 : The State-of-the-art Today
Facilities & Scientific Frontiers

2024 : The onset of 30-m class Telescopes
Instruments & Scientific Frontiers

2028 : The likely Reality, a decade from now
Facilities & Scientific Frontiers
Only One Planetary System in 1989

- Nine major planets
- The Kuiper belt was inferred, but no members yet detected
- Several cometary parent volatiles had been detected: $\text{H}_2\text{O}, \text{CO}_2, \text{H}_2\text{CO}, \text{CO}, \text{S}_2$
- No specific cometary minerals had been identified
- Safronov’s view of Oort cloud origin prevailed
- Cameron/Hayashi view of protoplanetary disk prevailed
- Exoplanets were sought but not yet detected
Advent of large (Vis-IR) ground-based telescopes

- 1993 - Keck 1, 10 m, Mauna Kea, Hawaii.
- 1996 - Keck 2, 10 m, Mauna Kea, Hawaii.
- 1997 - Hobby Eberly, 9.2 m, McDonald Observatory, Texas.
- 1998 - VLT1 (Antu), 8.2 m ESO, Paranal, Chile.
- 1999 - Subaru - 8.3 m NAO Japan, Mauna Kea, Hawaii.
- 1999 - VLT2 (Kueyen), 8.2 m ESO, Paranal, Chile.
- 1999 - Gemini North (Gillett), 8.1 m, Mauna Kea, Hawaii.
- 1999 - MMT, 6.5 m primary installed, Mt. Hopkins, Arizona.
- 2000 - VLT 3 (Melipal), 8.2 m ESO, Paranal, Chile.
- 2000 - Magellan 1 (Baade), 6.5 m, Las Campanas, Chile.
- 2001 - VLT 4 (Yepun), 8.2 m ESO, Paranal, Chile.
- 2001 - Gemini South, 8.1 m, Cerro Pachon, Chile.
- 2002 - Magellan 2 (Clay), 6.5 m, Las Campanas, Chile.
- 2001 - Keck Interferometer. Single-baseline operations begin in NIR.
- 2001 - VLTI interferometer. Single-baseline operations begin in NIR.
- 2003 - Large Zenith Telescope, 6 m, British Columbia.
- 2005 - VLTI using AMBER optical aperture synthesis and three VLT telescopes.
- 2005 - Southern African Large Telescope, 11 m, South Africa.
- 2007 - Gran Telescopio Canarias, 10.4 m, Canary Islands.
- 2007 - Large Binocular Telescope, 2 x 8.4 m, Mount Graham, Arizona.
Status of Planetary Systems in 2018

- Solar system has eight major planets; Pluto now an ice dwarf.
- > 1000s of Kuiper belt members detected; orbits for many, dynamical KB structure defined; Pluto-Charon explored

✓ Nice & Grand Tack models; origin of scattered Kuiper disk & LHB
- Quants in >40 active comets: Several dozen parent volatiles detected
  A taxonomy based on primary volatiles is emerging
  Crystalline and amorphous silicates identified in many comets
  Samples returned from 81P/Wild-2; exploration of 9P, 103P, 67P

✓ New view: active protoplanetary disk (chemical gradients, transport)
- Exoplanets found around >1000s of stars; many systems are multiple

✓ New models formed for origins of planets and Planetary Systems
Our Planetary System Today

- - - Rocky worlds - - -
- - - - Gas Giants - - - -

Ice Dwarfs ==>
Elliot et al. 2005
Imaging

Keck

Spectroscopy

C/2004 Q2 (Machholz), UT 2005 Jan 19.2, KL2

Order and principal molecules

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Wavelength

Range

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Order

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<td>26</td>
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2018 Synopsis: Cometary measurements in the near-IR spectral region (3-5 μm)

- Simultaneous or nearly-simultaneous sampling of 10 parent volatiles: H₂O, OH*, CH₄, C₂H₂, C₂H₆, CO, H₂CO, CH₃OH, HCN, NH₃, CO₂, etc.
- Direct detection of H₂O (non-resonant fluorescence). Ortho- and para-spin species.
- Unique sounding of symmetric species CH₄, C₂H₂, C₂H₆, ...
- Efficient measurement of rotational distributions (T_{rot}).
- Measurement of ortho-para ratios and spin temperatures.
- Measurement of HDO, CH₃D, DCN now feasible.

- Several classes of comets, based on organic volatile composition.
- Members of each class in both reservoirs (Oort cloud and Kuiper Belt)
- Strong variation in hypervolatiles (CO and CH₄) among comets.
- IR D/H in water measured (so far) only for 2 comets.
The timeline in 2008: Large Space and Ground-based Telescopes Expected by 2018

- 2009 - Herschel launched (3.5 m); sub-mm spectroscopy from L2.
- 2009 - SOFIA Airborne Observatory (3 m) achieves first light; now -
  EXES (4.5-28.3 μm, R~10^3-10^5); HIRMES (25-122 μm, R~325-10^5);
  GREAT (63 – 612 μm, R~10^6-10^8); low-res spectra & imaging.
- 2009 - Atacama Large Millimeter Array (ALMA); mm spectral images
- 2009 - Large Millimeter Telescope (50 m) (Mexico)
- 2013 - James Webb Space Telescope launch (6.6 m);
  0.6 - 27 μm spectroscopy and imaging, from L2.
- 2015 - Giant Magellan Telescope (23 m) (Las Campanas, Chile);
  1st segment cast 2007.
- 2015 - TMT (30 m) (Mauna Kea, or Chile).
- 2018 - E-ELT (39 m) (Chile, Canary Islands, etc.).
Sub-mm Molecular Astronomy
3.5 m primary

OBJECTIVES:
Study the formation of galaxies in the early universe and their subsequent evolution

Investigate the creation of stars and their interaction with the interstellar medium

Observe the chemical composition of the atmospheres and surfaces of comets, planets and satellites

Examine the molecular chemistry of the universe

**ORBIT: Earth-Sun L2**

**LAUNCHED:** 2009
**MISSION ENDED:** 2013
**LAUNCH VEHICLE:** Ariane-5
**LAUNCH MASS:** 3300 kg
**MISSION PHASE:** Implementation
NIR to Mid-IR (0.6 - 27 µm)
6.6 m primary

OBJECTIVES:
First Light and Re-ionization
The Assembly of Galaxies
The Birth of Stars and Protoplanetary Systems
Planetary Systems and the Origins of Life

ORBIT: Earth-Sun L2

LAUNCH DATE: 2013 2019 2021
MISSION END: 2023+ 2028+ 2030+
LAUNCH VEHICLE: Ariane-5
LAUNCH MASS: 6500 kg
MISSION PHASE: Implementation
JWST will measure minerals and ices in many TNOs

Fig. 1. Reflectance spectra of laboratory methane ice, Pluto (Grundy & Fink, 1996), and 2005 FY9. Spectra are normalized at 0.6\(\mu\)m and vertically shifted for clarity. Pluto and 2005 FY9 show very similar chemical surface composition. Figure from Licandro et al. (2006).
JWST will measure H$_2$O, CO, & CO$_2$ in a few active comets

Discriminating Ices from Gases

G. Blake et al. 2003 (personal communication)

Extend to: CO$_2$, H$_2$O, CH$_4$, C$_2$H$_2$, HCN, PAH, etc.
Large Space and Ground-based Telescopes by 2018-2028

2009 - 2010 - SOFIA Airborne Observatory (3 m) achieves first light.
  - 2010 - E-ELT (39 m) site selected (Cerro Armazones, Chile).

2009 - 2013 - Atacama Large Millimeter (& sub-mm) Array (ALMA); 1st comet spectra.
  - 2014 - E-ELT (39 m) Ground-breaking Ceremony.

2009 - 2017 - Large Millimeter Telescope (50 m) (Mexico) – final segments emplaced.


2015 - 2023 - Giant Magellan Telescope (23 m) operational (Las Campanas, Chile);
  1st mirror segment cast 2007.

2018 - 2024 - E-ELT (39 m) First Light planned (Cerro Armazones, Chile).

2015 - 2027 - TMT (30 m) (Mauna Kea; pending decision by Hawaii Supreme Court);
  alternate site is Observatorio del Roque de los Muchachos (La Palma).
**iSHELL @NASA/IRTF**

- **Year:** 2016
- **Diameter:** 3.0 m
- **Wavelength Coverage:** (1.1 – 5.3) µm
- **R:** 75,000

**CRIRES+ @ESO VLT**

- **Year:** 2018/19
- **Diameter:** 8.2 m
- **Wavelength Coverage:** (1 - 5.3) µm
- **R:** ~100,000

**NIRSPEC+ @Keck2**

- **Year:** 2019
- **Diameter:** 10 m
- **Wavelength Coverage:** (1 - 5.4) µm
- **Spectral Resolution:** ~37,000
**ESO E-ELT (Chile)**
D = 39 m
Wavelength Coverage: Optical to 2.5 µm
Moderate resolution
HARMONI, MICADO, AO

**GMT (Chile)**
D = 25 m
Wavelength Coverage: Optical to 2.5 µm
Four first light instruments. AO

**GMTNIRS @GMT**
D = 245 m
(1 – 5.3)µm
R: 50,000 - 100,000

**TMT (Hawai’i)**
D = 30 m
Wavelength Coverage: Optical to 2.5 µm
Moderate resolution
WFOS, IRMS, IRIS, AO

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**2023**

**2024**

**2027**

No high-res capability beyond 2.5 µm!

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2023 Status: Cometary measurements in the near-IR spectral region (3-5 µm)

- Parent volatiles quantified in another 20 comets: 15 OC & 5 JFCs
  \[ \text{H}_2\text{O}, \text{CH}_4, \text{C}_2\text{H}_2, \text{C}_2\text{H}_6, \text{CO}, \text{H}_2\text{CO}, \text{CH}_3\text{OH}, \text{HCN}, \text{NH}_3, \text{etc.} \]
- Deeper detections achieved in a few very bright comets; new species detected (\text{C}_2\text{H}_4, \text{C}_2\text{N}_2, \ldots)
  \[ \text{CH}_4, \text{C}_2\text{H}_2, \text{C}_2\text{H}_6, \text{CO}, \text{H}_2\text{CO}, \text{CH}_3\text{OH}, \text{HCN}, \text{NH}_3, \text{etc.} \]
  \textbf{Isotopomers:} D, \text{^{13}C}, \text{^{15}N}, \text{^{18}O}, \text{etc.}
- Measurement of ortho-para ratios and spin temperatures for H\textsubscript{2}O, CH\textsubscript{4}, NH\textsubscript{3}, H\textsubscript{2}CO, C\textsubscript{2}H\textsubscript{2}, etc.
- Measurement of HDO, CH\textsubscript{3}D, DCN in bright comets.

- Organic classes of comets tested; statistics improved.
- Improve statistics of class representations in OC and JFCs
- Correlations of more volatiles tested (C\textsubscript{2}H\textsubscript{4}, CH\textsubscript{4}, NH\textsubscript{3}, \ldots)
- Correlation of Spin Temperatures with organic class tested
- Measure HDO/H\textsubscript{2}O in one JFC and in 5-10 OCCs
- Test nucleus heterogeneity & binarity in multiple comets
Frontiers of High-R Spectroscopy in 2023, 3-5μm region:

Only iSHELL, NIRSPEC+, and CRIRES+ offer long-slit R~100,000 spectra. GMTNIRS offers short-slit R~100,000.

Establish statistically significant taxonomies for JFCs, HTCs, and OCCs. Target gases in Solar System Planets, and in Exoplanets

Isotopes: D/H, ¹⁴N/¹⁵N, ¹²C/¹³C, ¹⁶O/¹⁸O etc. (10 - σ on VSMOW D/H)

Nuclear Spin Isomers: CH₄, H₂CO, C₂H₂, etc.

Chemical Isomers: HNC, HCN, etc.

Trace chemicals: C₂H₄, C₃H₈, etc.

Nuclear Heterogeneity: jets, time-serial spectroscopy

Gas-grain precursors: extended sources
Frontiers of High-R Spectroscopy in 2023, 1-2.5 µm region:

Target gases in Exoplanets and TNOs
  Radial Velocities
  Atmospheric properties

E-ELT, GMT, and TMT offer short-slit R~100,000 spectra. IRTF and Keck offer longer-slit R~100,000 spectra.

AO-equipped large telescopes advance sensitivity limits for point sources by huge (areal) factors:

Diameter – 39m : 23m : 10m : 8m : 3m

Area – 1194 m² : 415 m² : 78 m² : 50 m² : 7 m²

Match pixels to $A\Omega = \lambda^2/4$

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Evolution of High-R Astronomical Sensing Speed 1996-2027 in the range 1-5 µm.

<table>
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<tr>
<th>Array</th>
<th>Detector</th>
<th>Speed.</th>
<th>Focal plane advantage</th>
<th>Aperture Diameter</th>
<th>Area</th>
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Although currently leading the field, IRTF will need to implement AO to remain competitive. When daytime observing is required, IRTF is UNIQUE. NASA needs ground-based facilities to support the nation’s space missions – before, during, and after they occur.

*iGRINS addresses H and K bands only. The values are for iGRINS at McDonald; it has since moved to Gemini North and is now moving to the Discovery Channel Telescope.

**The number of settings needed for a given band increases with R; this effect has not been included here.
End