SPHEREx: An All-Sky Spectral Survey

Designed to Explore
- The Origin of the Universe
- The Origin and History of Galaxies
- The Origin of Water in Planetary Systems

The First All-Sky Near-IR Spectral Survey
A Rich Legacy Archive for the Astronomy Community with 100s of Millions of Stars and Galaxies

Low-Risk Implementation
SPHEREx: Major Science Themes

SPHEREx provides a galaxy redshift survey with the largest cosmological volume by mapping the entire sky, increasing by >100 the number of ice spectra. SPHEREx provides a unique deep survey to measure large-scale structure in multiple bands.

Tests cosmic inflation by improving errors on the non-Gaussianity parameter $f_{NL}$ by $>10 \times$. Uses two independent measurements: power spectrum and bispectrum.

Low redshift coverage provides strong scientific synergies with Euclid and WFIRST. Determines the abundance of water and other biogenic ices. Probes the production of ices in young stellar and planetary systems. Anisotropy measurement tests galaxy luminosity history. Synergies with deep surveys that count individual galaxies. Probes luminosity of the first galaxies formed.

Figure D.1 - SPHEREx's three core science themes. Left: SPHEREx will study the nature of the inflationary expansion in the early universe by mapping the 3-D distribution of galaxies. Center: SPHEREx will determine the role of interstellar ices, thought to be a key reservoir in water and biogenic molecules for the evolution of life in our solar system, in the early phases of the formation of exoplanetary systems. Right: SPHEREx will probe the history of galaxy formation, from the first galaxies to form from primordial matter and ignite the first stars, to modern galaxies.

Probe the earliest epochs in the Universe's history

Surveys the ice content throughout the Milky Way

Measures the history of light production and constrain galaxy formation

Jamie Bock, PI
Olivier Dore
Caltech

Gary Melnick
Harvard & Smithsonian

Asantha Cooray
UC, Irvine
More than 99% of interstellar water is locked in ice, so...
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‘Follow the Water’ really means ‘Follow the Ice’
SPHEREx Will Survey Ices in All Phases of Star Formation via Absorption Spectroscopy

Dense Clouds
Young Stellar Envelopes
Protoplanetary Disks
Young Solar Systems
SPHEREx will measure ice column densities toward >> 20,000 sources and determine how water and biogenic ices evolve from molecular clouds to young stars to protoplanetary disks.
SPHEREx: Top-Level Summary

- 20-cm telescope effective diameter
- 0.75 – 5.0 µm wavelength range
- Passively cooled, background limited
- $\lambda/\Delta\lambda = 35 – 130$ resolving power
- 3.5° x 11.3° field of view
- 6.2” pixel size (13.9 billion spectra)

Sensitivity

Point: 18.4 AB mag ($5\sigma @ 2 \mu m$)
Surface: 4.5 kJy/sr ($1\sigma @ 1.1 \mu m$)

- High S/N spectrum for every 2MASS source (~ 4 mag deeper than 2MASS)
- Solid detection of faintest WISE sources
SPHEREx’s 28-gm spectrometers

3-Mirror Astigmat

- High-Throughput LVF Spectrometer
- Spectra obtained by stepping source over the FOV in multiple images: no moving parts

Used on:
- ISOCAM
- HST-WFPC2
- New Horizon
- LEISA
- OSIRIX-Rex

Wavelength (µm)
- 1.6
- 1.8
- 2.0
- 2.2
- 2.4

I/F
- 1.0
- 0.8
- 0.6
- 0.4
- 0.2
- 0.0

Methane on Pluto

Infrared Spectral Image
SPHEREx will conduct an all-sky spectroscopic survey between 0.75 – 5.0 µm

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- Baseline 2-year mission
  - 4 independent all-sky surveys
  - 13.7 billion positions per survey, each with spectra
  - No expendables
SPHEREx Operates in 6 Spectral Bands Between 0.75 – 5 µm

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength</th>
<th>Resolution</th>
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<tbody>
<tr>
<td>1</td>
<td>0.75 µm</td>
<td>R = 41</td>
</tr>
<tr>
<td>2</td>
<td>1.11 µm</td>
<td>R = 41</td>
</tr>
<tr>
<td>3</td>
<td>1.64 µm</td>
<td>R = 41</td>
</tr>
<tr>
<td>4</td>
<td>2.42 µm</td>
<td>R = 35</td>
</tr>
<tr>
<td>5</td>
<td>3.82 µm</td>
<td>R = 110</td>
</tr>
<tr>
<td>6</td>
<td>4.42 µm</td>
<td>R = 130</td>
</tr>
<tr>
<td>7</td>
<td>5.00 µm</td>
<td></td>
</tr>
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This is where the gold is buried (for ices)
The 2.5-5 µm range is particularly rich in ice features.
SPHEREx is designed to permit spectral isolation of ice features ISO absorption spectra toward Galactic star forming regions in black, obtained with $R > 700$.
In order to understand the relation between the measured ice composition and such factors as…

- Cloud density
- Internal temperature variations
- Starless cores or clouds with embedded sources
- External far-ultraviolet flux
- External x-ray flux
- Elemental abundances (e.g., Galactic C/O gradient)
- Gas-phase molecular composition
- Cosmic-ray ionization rate
- Cloud age (if possible to estimate)
- Other?

A large sample of spectra is needed.
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Unfortunately, ISO, Spitzer, and AKARI have only published spectra toward a total of ~200 lines of sight…

…too few to enable the type of statistically significant studies needed to relate cloud properties to ice composition and distribution.
SPHEREx will increase the number of high-quality ice absorption spectra by at least 100-fold (and likely > 1,000 fold)
But to ‘map’ the Galaxy in ice absorption, a large number of background sources are required.
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Fortunately, nature provides these background sources in great abundance.
Between

$-180^\circ \leq \epsilon_\Pi \leq +180^\circ$

$-5^\circ \leq \epsilon_\Pi \leq +5^\circ$

Distribution of molecular gas in the Milky Way

Planck
$^{12}\text{CO J}=1-0$

$\pm 5^\circ$
Between $-180^\circ \leq \ell_{\mathrm{II}} \leq +180^\circ$ and $-5^\circ \leq \ell_{\mathrm{II}} \leq +5^\circ$ there are...

- $\geq 4 \times 10^7$ 3.4 µm WISE point sources $> 1$ mJy
- $\geq 3 \times 10^7$ 4.6 µm WISE point sources $> 1$ mJy

Distribution of molecular gas in the Milky Way

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To be considered a ‘good’ background source, 3 criteria must be met:

1) To ensure a background source is spatially isolated (i.e., no confusion), there can be no other WISE source within ± 6.2 arcsec with more than 1% of its flux density.
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   - Use is made of 2MASS H- and K-band data + WISE 3.4 µm (W1) and WISE 4.6 µm (W2) data.
   (Intervening extinction is inferred if: H-W2 > 1.55 and K-W1 < 0.7)
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3) The catalogued flux density of the background point source would result in a signal-to-noise ratio ≥ 100 per SPHEREx spectral resolution element (Δλ).
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SPHEREx will be a game changer for the study of ices by…

After Boogert et al. 2015

... revealing the relation between ice column density and $A_V$ within molecular clouds
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By sampling orders of magnitude more lines of sight, SPHEREx will add significantly to our knowledge of both the depths at which ices form, and their relative abundances as a function of cloud depth.

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⇒ SPHEREx can provide a target list of interesting sources for JWST follow-up.
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⇒ SPHEREx can provide a target list of interesting sources for JWST follow-up.

— JWST is not a survey telescope and, thus, cannot produce the extensive and unbiased catalog of spectra possible with SPHEREx.

— However, JWST’s ability to cover 0.6 – 28 µm (0.6–5 µm, R ≥ 1000 with NIRSpec; 4.6–28.6 µm, R~3000 with MIRI) can provide valuable follow up of select SPHEREx results.
Launch is currently scheduled for September 2023.
The 2.5-5 μm range is particularly rich in ice features

## Ice Features Between 2.9 and 4.9 μm

<table>
<thead>
<tr>
<th>Molecule</th>
<th>(\lambda) (μm)</th>
<th>(\Delta\nu) (cm(^{-1}))</th>
<th>Vibration Mode</th>
<th>(A) (10(^{-17}) cm molecule(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{NH}_3)</td>
<td>2.96</td>
<td>45</td>
<td>–N–H stretch</td>
<td>1.1</td>
</tr>
<tr>
<td>(\text{H}_2\text{O})</td>
<td>3.05</td>
<td>335</td>
<td>O–H stretch</td>
<td>20</td>
</tr>
<tr>
<td>–CH(_2\–), –CH(_3) –</td>
<td>3.47</td>
<td>~ 10</td>
<td>C–H stretch</td>
<td>~ 0.1 – 0.4</td>
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<tr>
<td>(\text{CH}_3\text{OH})</td>
<td>3.53</td>
<td>30</td>
<td>C–H stretch</td>
<td>0.76</td>
</tr>
<tr>
<td>(\text{CH}_3\text{OH})</td>
<td>3.95</td>
<td>115.3</td>
<td>C–H stretch</td>
<td>0.51</td>
</tr>
<tr>
<td>(\text{H}_2\text{S})</td>
<td>3.95</td>
<td>45</td>
<td>S–H stretch</td>
<td>2.9</td>
</tr>
<tr>
<td>(\text{CO}_2)</td>
<td>4.27</td>
<td>18</td>
<td>C–O stretch</td>
<td>7.6</td>
</tr>
<tr>
<td>(\text{^{13}CO}_2)</td>
<td>4.38</td>
<td>12.9</td>
<td>(^{13})C–O stretch</td>
<td>7.8</td>
</tr>
<tr>
<td>(\text{H}_2\text{O})</td>
<td>4.5</td>
<td>700</td>
<td>(3\nu_L) and/or (\nu_2 + \nu_L)</td>
<td>1.0</td>
</tr>
<tr>
<td>“XCN”</td>
<td>4.62</td>
<td>29.1</td>
<td>CN stretch</td>
<td>~ 5</td>
</tr>
<tr>
<td>(\text{CO})</td>
<td>4.67</td>
<td>9.71</td>
<td>(^{12})CO stretch</td>
<td>1.1</td>
</tr>
<tr>
<td>(\text{^{13}CO})</td>
<td>4.78</td>
<td>19.6</td>
<td>(^{13})CO stretch</td>
<td>1.3</td>
</tr>
<tr>
<td>(\text{OCS})</td>
<td>4.91</td>
<td>19.6</td>
<td>C–S stretch</td>
<td>17</td>
</tr>
</tbody>
</table>