EXES: The Echelon-Cross-Echelle Spectrograph for SOFIA - An Update

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Introduction

SOFIA's Echelon-Cross-Echelle Spectrograph (EXES) is a first-generation flight science instrument scheduled for commissioning in 2013. A UC Davis/NASA ARC team is developing this instrument for astronomical observations in three spectroscopic modes (R~10^5, 10^4, and 3000) at wavelengths from 5 -28 μm. EXES uses a 1024x1024-element Si:As BIB detector to capitalize on SOFIA's unique potential for high resolution spectroscopy in the mid-infrared. High dispersion is provided by an echelon, a coarsely-ruled, steeply-blazed aluminum reflection grating cross-dispersed by an echelle grating to provide continuous wavelength coverage of ~10 cm^{-1} and a slit length of ~10" at R=10^5. Optionally, the echelon can be bypassed so that the echelle or a low order grating acts as the sole dispersive element. This results in a single order spectrum with slit length of roughly 90" and R=10,000 or 3000, respectively. The low resolution grating also serves as a slit positioning camera when it is rotated face on. Recent laboratory tests have demonstrated spectral resolution of 1.1x10^5 at 14μm in preparation for ground-based observations from NASA's IRTF (Mauna Kea, HI) in January 2011.

EXES Science

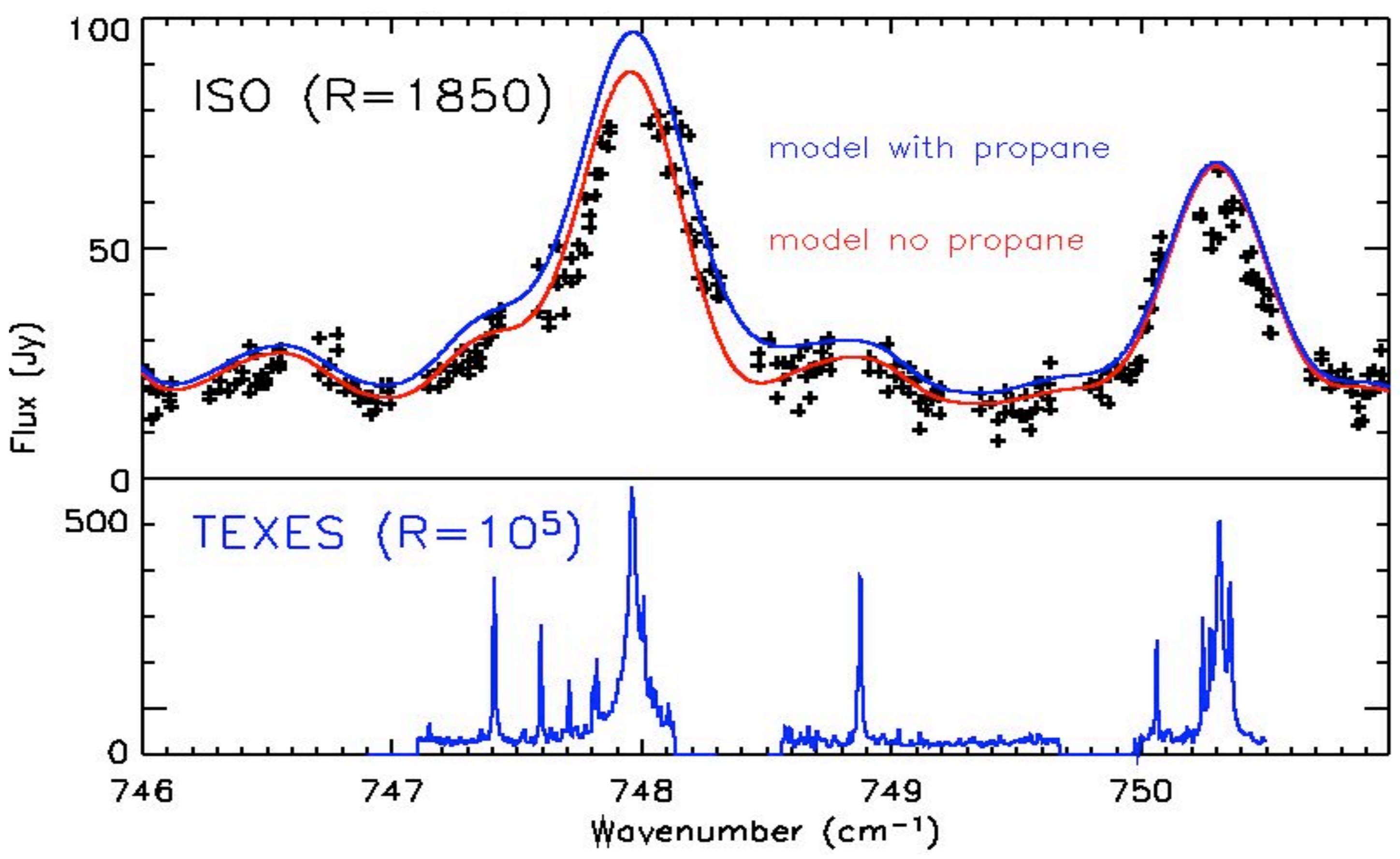
The main emphasis for EXES is the study of molecular gas in the mid-infrared spectral region, where nearly all the important vibrational modes of common astrophysical molecules reside. Even symmetric molecules such as H_2, CH_4, and C_2H_2, which have no dipole moment for rotational transitions available in the radio can be studied in the mid-infrared. EXES' high spectral resolution is well matched for low pressure environments in the solar system, for cold quiescent gas in the ISM, and for studying dynamics using velocity information within the line profile in regions such as star forming regions, protoplanetary disks, and PDRs. As EXES will be background-limited, binning to lower resolving power so as to match the actual line width will provide the best sensitivity for detection experiments. The lower resolution modes are better suited for studying gas in shocks and external galaxies, where velocities are large, and for looking at solid-state features such as ices and PAHs. EXES is not optimized for lower resolution observations – an optimized instrument would have larger wavelength coverage – but it will permit observations unsuitable for FORCAST grisms.

Unique and Complementary: EXES exploits the strengths of SOFIA to provide science available from no other platform, and science that strongly leverages its complementarity with other space- and ground-based astronomical assets. JWST/MIRI's larger cryogenic telescope will provide superior point source sensitivity, but will be unable to recover velocity information below 100 km/s at its R=3000 resolving power. Weak, narrow features will also be harder to detect with MIRI due to dilution from the continuum. Spitzer's IRS also benefitted from cold-telescope sensitivity, but with a maximum resolving power of R=600. Herschel operates at longer wavelengths where molecules do not have ro-vibrational transitions. Ground-based instruments are severely hampered by the terrestrial atmosphere over much of the wavelength region, where telluric features not only absorb light from the object, but add significantly to background noise. At SOFIA's altitude residual atmospheric lines, with the exception of the 9.7 μm O_3 band and the 15 μm CO_2 band, are narrow enough that Earth's 30 km/s Doppler shift due to orbital motion is sufficient to permit observations. SOFIA/EXES provides an unmatched combination of spectral resolution, sensitivity, and sky/spectral coverage that will create both new discovery and a powerful tool to enhance science return through follow-up on discoveries made with other instruments.

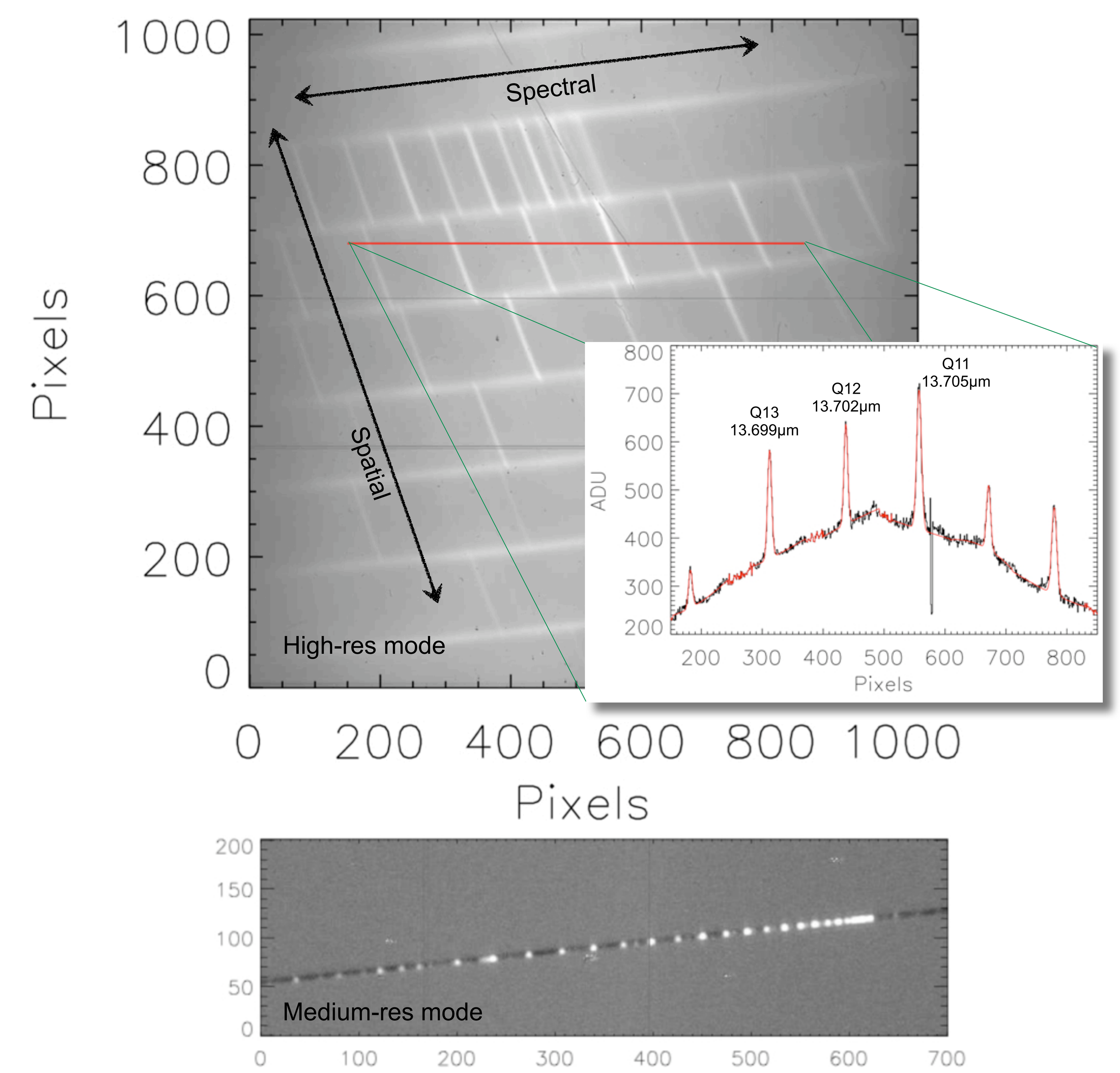
Some examples of anticipated early EXES science include:

- *Regular monitoring of Martian CH_4:* Recent near-IR observations find Mars has spatially and temporally variable methane. The lifetime of methane in the Martian atmosphere (<1 year) requires regular production of new methane, potentially from biotic processes. EXES will be able to observe the stronger 7.7 μm band of CH_4 and provide superior seasonal coverage.
- *H_2O in star formation regions:* H_2O is a simple, abundant, and important molecule in regions of star formation, and is difficult to study from the ground due to Earth's atmosphere. ISO spectral observations, for essentially the first time, showed that H_2O can be used to study preferentially the physical conditions close to massive star forming regions where ice has evaporated. EXES on SOFIA will be able to utilize the same H_2O features to determine abundances and temperatures, identify multiple components through velocity structure, and relate H_2O to other molecules such as CO and H_2.
- *The Study of H_2:* The molecular physics governing H_2 results in rotational transitions in the mid-IR. While three low-excitation energy, pure rotational lines are available from the ground, significant atmospheric absorption is present even from Mauna Kea. From SOFIA EXES will be able to observe the J=3-1 and J=7-5 lines with essentially no telluric interference. These improved diagnostics will enable EXES to study H_2 more effectively wherever it is found: giant planets, PDRs, slow shocks in the general ISM, mass-loss stars, and external galaxies.

EXES and SOFIA



Why High Resolution Matters *(above): A comparison of ISO observations with ground-based observations with EXES' sister instrument TEXES for detection of propane in Titan's atmosphere (see Roe et al. 2003) EXES performance from the SOFIA platform will exceed that of TEXES.*



Lab Spectra*: C_2H_2 low-pressure gas cell spectra obtained with EXES. Hi-res mode (above) gives R=110k @ 13.7μm and best spectral focus. Medium-res mode (below) demonstrates background- and diffraction limited performance in EXES.*

EXES Development Status

After major instrument hardware development at the University of Texas, EXES was transferred to NASA Ames Research Center in July 2009 for completion. EXES is a collaboration led by PI Matt Richter of UC Davis. Ames contributes the detector array plus engineering, test, and analysis support. *Six nights on the IRTF in January 2011 have been awarded for first-light astronomy from Mauna Kea.*

To date, six instrument cold cycles have been performed, characterizing and refining optical performance. A low-pressure laboratory gas cell containing a small amount of C_2H_2 provides a well-known calibration spectrum. Early results have demonstrated instrument performance that meets nearly all established science requirements.

Background- and diffraction-limited spectra have been obtained in EXES' medium-resolution mode. C_2H_2 spectra taken in high-resolution mode have demonstrated resolving power greater than 110,000 in the 13.7μm Q-branch vibration spectrum at best spectral focus. Tests have revealed astigmatism in high-res mode, limiting resolving power to ~65,000 at the circle of least confusion. The camera/collimator mirror in the echelon chamber is the most likely cause, and work is underway to confirm and correct the issue.

Bach Research will complete EXES' flight echelle grating by the second quarter of 2011. This grating will provide EXES with the ability to utilize all design science modes. Presently, EXES uses a 30/mm grating on loan from UT Austin. This temporary grating is performing well in high- and med-res modes, with slight limitations due to geometric constraints.

The EXES SB226 megapixel Si:As IBC detector array, purpose-built for low-background astronomy by Raytheon Vision Systems under contract to Ames, delivers performance in EXES on par with previous lab characterization data obtained using different, optimized, low-background cryostats and drive electronics, lending confidence that the instrument design and electronics implementation are sound. Present detector development efforts focus on specialized clocking modes optimized for higher photon backgrounds in EXES low- and medium-resolution observing modes.

FORCAST-heritage drive and digitization electronics have been adapted for EXES. This approach cost-effectively leverages SOFIA investments in FORCAST development, plus commonalities in software (MCCS, DCS, instrument code) and hardware airworthiness certification.

Two smaller test dewars, wired identically and containing identical detector mounts provide for parallel detector testing, decoupling software and hardware development from the longer thermal cycle times of the large instrument cryostat. A test series on an alternate detector based on the RVS SB291 megapixel readout is underway at Ames to establish a robust backup detector strategy as risk mitigation.

Sensitivity*: Calculation of 10σ:900s sensitivity per resolution element from SOFIA including median atmospheric transmission in 0.025 micron bins*