High-resolution Mid-IR Observations of the Molecular Universe with EXES on SOFIA

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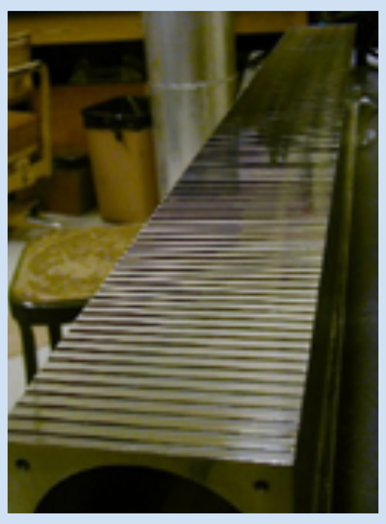
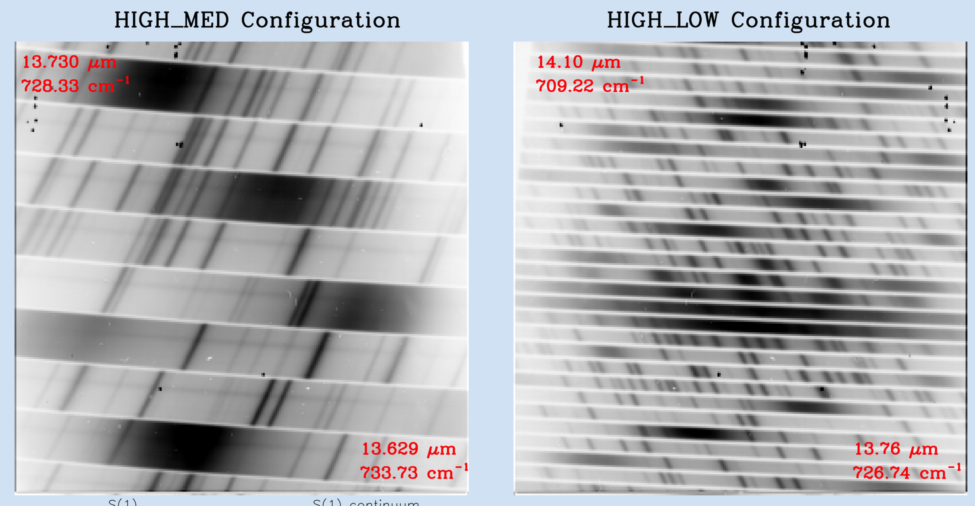
What is EXES?

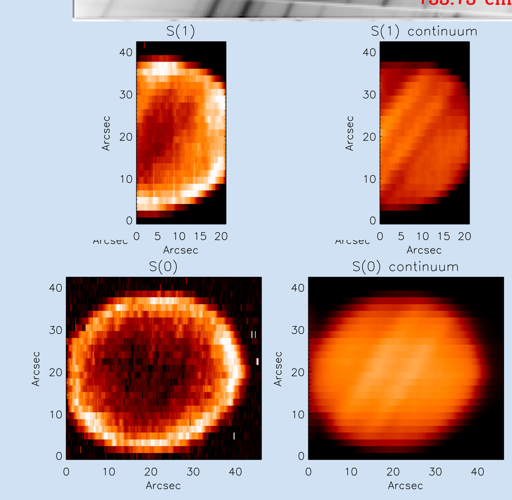
- Mid-IR High-Resolution spectrograph for SOFIA
- 1024 x 1024 Si:As detector
- 4.5 - 28.3 μm range
- 0.5-4% spectral coverage per setting, depending on choice of cross-disperser and spatial slit length
- Three spectral modes: high (R=100,000) medium (R=15000) and low (R=3000)
- Observing modes: nodding & mapping



The Al R10 echelon grating for EXES (40” x 4”) provides the high dispersion power



In the high-resolution cross-dispersed modes, trade-offs can be made between wavelength coverage and slit length

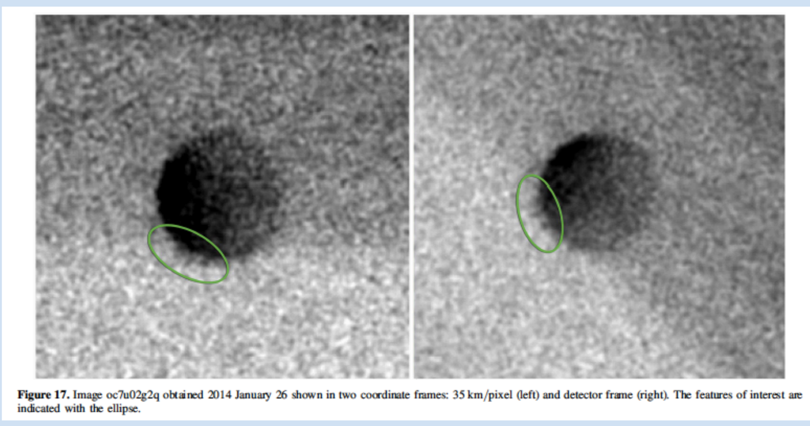


2-D spectral maps are produced by scanning the slit position across an extended source. Here is shown the line emission and continuum maps of Jupiter for H_2 S(1) at 17 μm and H_2 S(0) at 28 μm.

Search for Europa’s ice plumes at 6.1 μm

- EXES has set useful upper limits for 3 strong ro-vibrational transitions of water near 6.1 um including the H_2O ν_2 $1_{1,1}$-$0_{0,0}$ line in March and May 2017, covering the leading and trailing side hemispheres of Europa.

*The limits for both dates and hemispheres depend on the assumed gas temperature – for reasonable values seen in cometary gas of 10-100K, the upper limits for numbers of H_2O molecule are ~$5x10^{31}$ (10K) - ~$5x10^{32}$ (100K); the implied number of molecules from the HST/STIS transit observations is ~1-2 x 10^{32}.

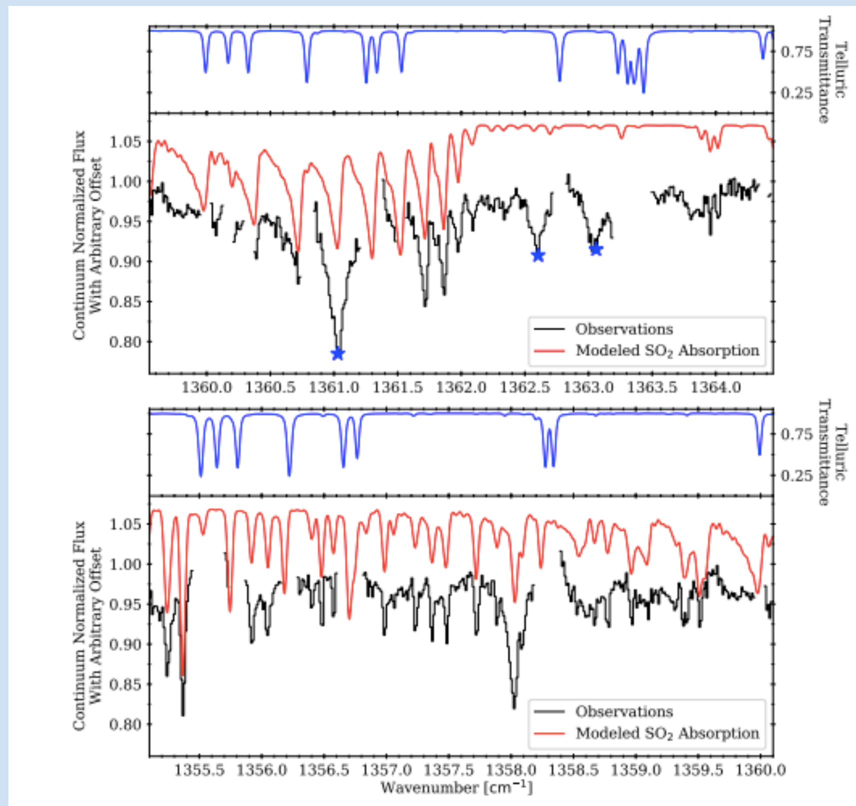


Water plumes detected by HST/STIS FUV absorption against Jupiter (Sparks et al. 2016)

Sparks, et al. *“A Search for Water Plumes on Europa with SOFIA”*. 2019, ApJL, *in press*

SO_2 gas towards the massive YSO Mon R2 IRS 3

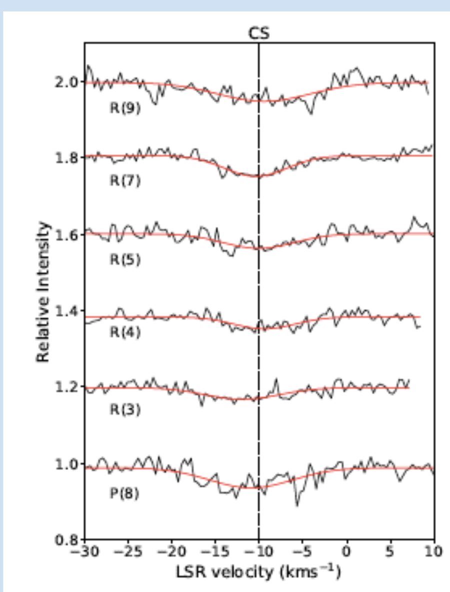
- In dense clouds and protostellar environments only a few percent of cosmic sulfur has been identified.
- EXES has resolved SO_2 bands previously seen by ISO, finding narrow line widths (<3.2km/s) and T=234 K, locating the gas in a quiescent region close to the protostellar core, where presumably, sulfur-bearing ices have been evaporated, and SO_2 has formed by warm gas-phase chemistry. SO_2 gas accounts for 6% of the sulfur budget.
- Similar work is underway for other hot cores with gas-phase SO_2 detections from ISO.

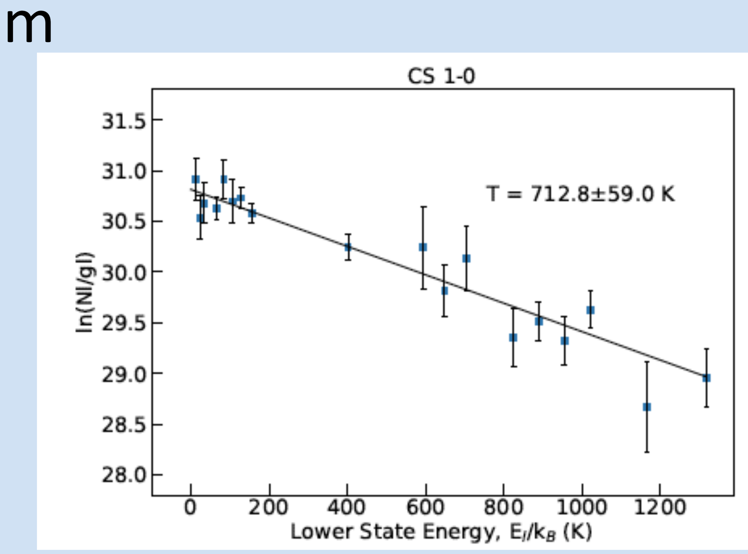


Dungee, et al. *“High Resolution SOFIA/EXES Spectroscopy of SO2 Gas in the Massive Young Stellar Object MonR2 IRS3: Implications for the Sulfur Budget”*. 2018, ApJL, 868, L10

CS in the hot core AFGL 2591

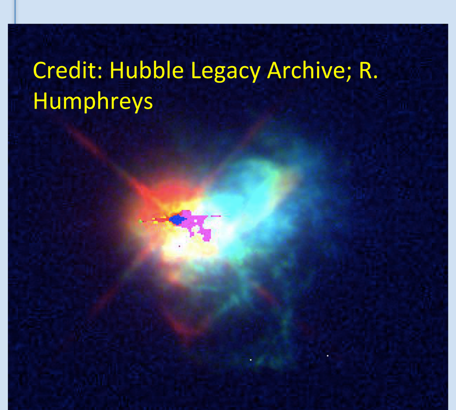
- 18 transitions of CS between R(3) – R(33) were detected by EXES as part of 5.5-8 um hot core spectral survey.
- Gas traces close to the inner envelope base of the outflow with H_2O and ^{13}CO and ^{12}CO gas also tracing the same component. T=712K, CS/^{12}CO = 0.008, 10x the submm value
- Submm CS traces a cooler, quiescent, more distant component.
- Enhanced CS/^{12}CO may arise from sublimation of H_2S ice and gas phase reactions resulting in CS.



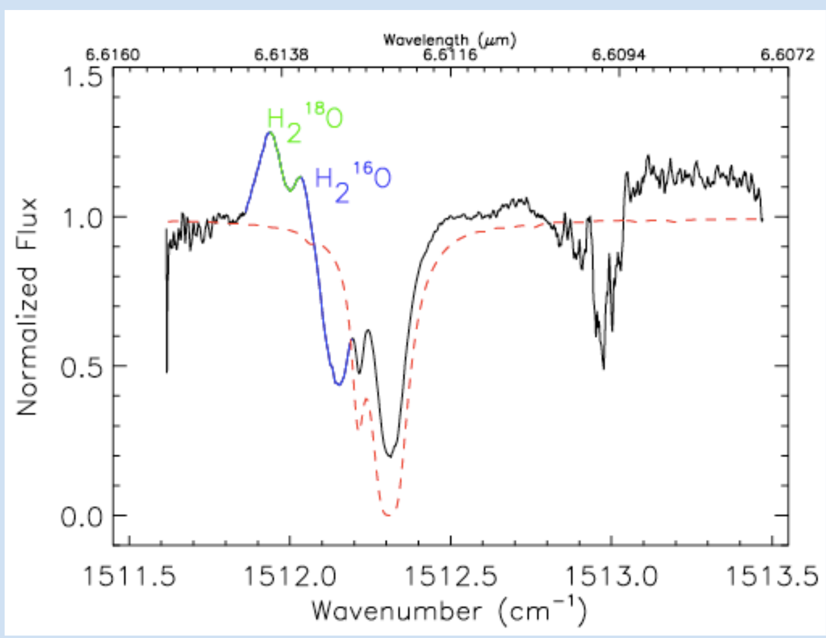


Barr, et al. *“Infrared Detection of Abundant CS in the Hot Core AFGL 2591 at High Resolution with SOFIA/EXES”*. 2018, ApJL, 868, L2

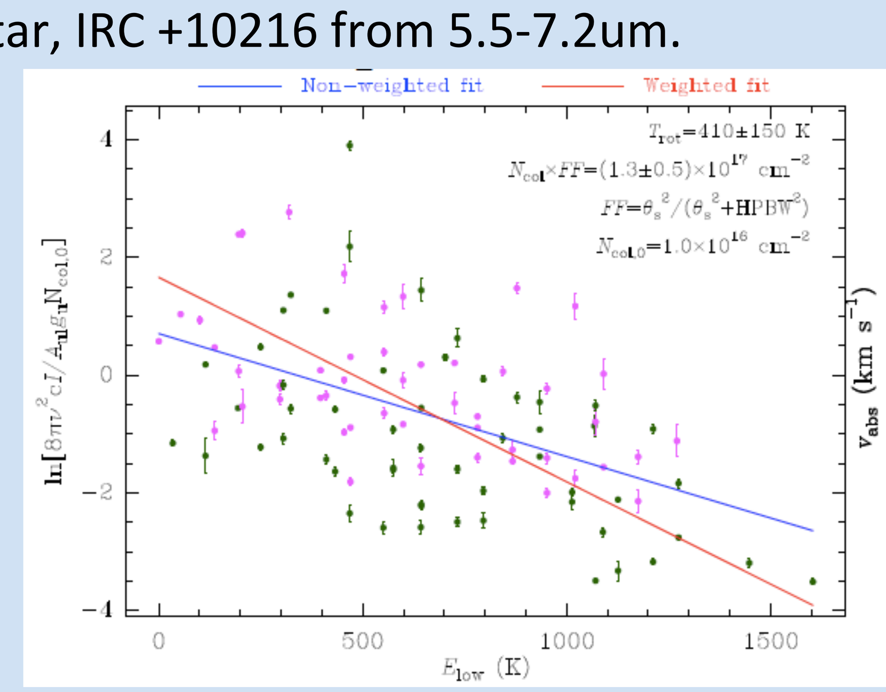
Mass-loss in the Red Supergiant VY CMa



VY CMa is an archetypal O-Rich red supergiant, M = 17 +/-8 $M_\odot$ and mass loss rate ~ 10^{-4} $M_\odot$/yr.
EXES has taken R=85000 spectra from 5.5-6.8um to probe the mass ejections and better understand the composition, chemistry, architecture and kinematics of the mass loss in these sources. The data set complements spectral survey data taken for the C-rich AGB star, IRC +10216 from 5.5-7.2um.



Subset of the 5.5-8um spectrum showing a P-Cygni water line profile as well as emission from $H_2^{18}O$. The red dashed line shows the telluric transmission.



The rotational diagram is complicated by extracting line strengths from P-Cygni profiles. A more complete radiative treatment is underway. (Montiel et al, 2019)

Future Flights and Observing Availability

- Cycle 7 (May 2019- Apr 2020) programs just announced. Cycle 8 (May 2020−) call for proposals in fall 2019. Directors Discretionary Time proposals (e.g. Jovian storms, comets) are accepted at any time.
- EXES exposure time calculator → http://irastro.physics.ucdavis.edu/exes/etc/
- Proposers are encouraged to contact EXES team for advice and assistance.
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