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MID–INFRARED SPECTROSCOPY WITH SOFIA, EXES, AND TEXES

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RESUMEN

Estamos construyendo dos espectrógrafos de alta resolución en el mediano infrarrojo. Ambos operan en 4-28 μm en tres modos espectroscópicos: en dispersión cruzada con R $\sim 10^5$, y en rendija larga con R $\sim 2 \times 10^4$ ó R $\sim$ 4000. Ambos instrumentos usan un echelon, una rejilla de difracción con un *blaze* muy prominente y con rallado grueso para lograr alta resolución.

ABSTRACT

We are building two high resolution, mid–infrared spectrographs; the Texas Echelon–cross–Echelle Spectrograph (TEXES) is designed for ground–based telescopes and the Echelon–cross–Echelle Spectrograph (EXES) is designed for the Stratospheric Observatory for Infrared Astronomy (SOFIA). Both spectrographs operate at 4-28 μm in three spectroscopic modes: a cross–dispersed mode with R $\sim 10^5$, and longslit modes with either R $\sim 2 \times 10^4$ or R $\sim$ 4000. Both instruments use an echelon, a coarsely ruled, steeply blazed diffraction grating, to achieve high resolution. These instruments will be well suited for the study of molecular lines in the cold interstellar medium, around young stars, and in planets.

Key Words: **INFRARED: ISM: LINES AND BANDS — INSTRUMENTATION: SPECTROGRAPHS — ISM: MOLECULES**

1. INTRODUCTION

Mid–infrared (MIR) spectroscopy has applications to a broad range of problems in planetary, stellar, interstellar, and extragalactic astrophysics. While it is true that the broadband night sky at 10 μm is brighter than the optical daytime sky, and that MIR detectors have orders of magnitude fewer pixels than optical CCDs or near infrared arrays, the fact that many molecules have MIR transitions makes high resolution, MIR spectroscopy an extremely valuable tool. And while the spectrum available from roughly 5 μm to 30 μm is limited by Earth's atmosphere, much of the band is accessible from the ground and even H_2O can be observed without a satellite.

We are building two MIR grating spectrographs with broad capabilities, but primarily focused on high resolution molecular observations. The Texas Echelon–cross–Echelle Spectrograph (TEXES) is designed for ground based telescopes and has had a successful commissioning run at the McDonald Observatory 2.7 m Harlan J. Smith Telescope. Our second spectrograph, the Echelon–cross–Echelle Spectrograph (EXES) is designed for the Stratospheric Observatory for Infrared Astronomy (SOFIA) and should be commissioned sometime in 2002 with a first flight in 2003. Both TEXES and EXES can easily switch between spectroscopic resolving powers of R=10^5, 2×10^4, and 4000. Although the highest resolution is best suited for studies of gas–phase molecular species, the medium and low resolution options are suitable for a range of other scientific projects. The detector for both instruments covers a wavelength range extending from about 4.5 μm to about 28.5 μm; within that range, atmospheric transmission determines what spectral lines are observable.

2. SCIENCE IN THE MIR

Many molecules have rotation and or rotation–vibration transitions in the MIR. Some examples include H_2, H_2O, CO, CH_4, C_2H_2, and NH_3. The symmetric molecules, H_2, CH_4, and C_2H_2, have no permanent dipole and so are not seen with radio telescopes. For typical molecular gas where the visual extinction is high, the only way to study these molecules is with infrared spectroscopy. One advantage of observing rotation–vibrational bands is that transitions spanning a range of excitation energies are often seen at a single wavelength setting.

The scientific usefulness of IR molecular spectroscopy has been demonstrated to the general astronomical community by the many exciting results from the Infrared Space Observatory (ISO). Some examples include measuring H_2 from disks around young stars (Thi et al. 1999), determining the column and temperature of gas–phase H_2O (Helmich et al. 1996) and other molecules through molecular clouds (?), looking at the chemistry in mass–loss stars (Cernicharo et al. 1999), characterizing planetary atmospheres (Fouchet et al. 2000), and examining shocks in molecular gas (Rosenthal, Bertoldi & Drapatz 2000). Because of ISO's limited lifetime, aperture, and spectral resolution, there are many questions raised by ISO that will require substantial follow–up observations.

Because ISO was best–suited for observing extended objects, TEXES and EXES should have a point–source sensitivity superior to ISO's in regions with good atmospheric transmission, as well as superior spectral and spatial resolution. Thus, one will be able to go beyond simple line strength analyses and actually study the kinematics of molecular gas as well as map out extended structures.

One example of TEXES's potential is the case of H_2 emission from the young quadruple system GG Tau. ISO detected H_2 emission, but was unable to constrain its location (Thi et al. 1999). With TEXES, we will be able to differentiate between emission from a circumprimary disk (< 20 AU of GG TauAa) and emission from the circumbinary disk (< 200 AU) based on the spectral width of the H_2 emission feature. In fact, it should be possible for TEXES to place the first constraints on the temperature structure in protostellar and protoplanetary disks at the interesting distances of 1–10 AU.

3. INSTRUMENT PROPERTIES

Two basic technological developments significantly affected the design of TEXES and EXES: diamond–machining techniques now allow fabrication of 1 meter long, monolithic aluminum diffraction gratings and large format MIR focal plane arrays are now available for use at low backgrounds.

The primary dispersive element in our spectrographs is an echelon, a coarsely ruled, steeply blazed diffraction grating (Michelson 1898). The echelon gratings for TEXES and EXES are ruled at R10 with 0.3 inch (7.5 mm) separation between grooves and with lengths of 36 inches (0.9 m) and 40 inches (1 m) long, respectively. Both gratings were manufactured by Hyperfine, Inc (Bach, Bach & Bach 2000). We operate in very high order: $\approx 1500^{th}$ at 10 μm. Because the free spectral range is small, the high resolution mode requires cross–dispersion with a second grating.

Our instruments can operate in four separate modes. Besides the high resolution, cross–dispersed mode using the echelon, we can bypass the echelon and use only the cross–dispersing grating. This allows a slit up to $60''$ long and a resolving power of either 20,000 or 4,000, depending on the choice of cross–disperser. In addition, the low resolution grating can be turned face–on for a camera suitable for locating objects.

The high resolution mode reduces the background such that we require a focal plane array with very low read noise. Therefore, we chose a 256^2 pixel array developed by Raytheon for use on SIRTF, which has a read noise of less than 30 e^-. It is a Si:As detector sensitive from ~ 4 μm to just past 28 μm. Typically, 8 orders land on the array in cross–dispersed format, giving a spectral coverage of approximately 5 cm^{-1}. For wavelengths shorter than 10 μm, the spectral coverage is continuous. A consequence of the low–background array is that the limited well–depth, $< 2 \times 10^5$ e^- per pixel, forces us to readout only part of the array for lower spectral resolution observations. There also seems to be increased noise at high flux levels.

We recently had an observing run with TEXES, our ground based instrument, at the McDonald Observatory 2.7 m Harlan J. Smith telescope (see Figure 1). During that run, we verified that all the observing modes worked. In particular, we achieved the design spectral resolution of R=100,000 in echelon mode. We are still in the process of reducing much of the data and expect to detail our results more fully in later publications (Lacy et al. 2001, in preparation). An example of our current pipeline reduction is seen in Figure 1, an observation of the mass–loss star VY CMa. We detect ro–vibrational transitions of SiO and its isotopes. The lines show P Cygni profiles, as seen before (Geballe, Lacy & Beck 1979). We also see three H_2O emission features. This plot represents about 5 minutes of integration time.

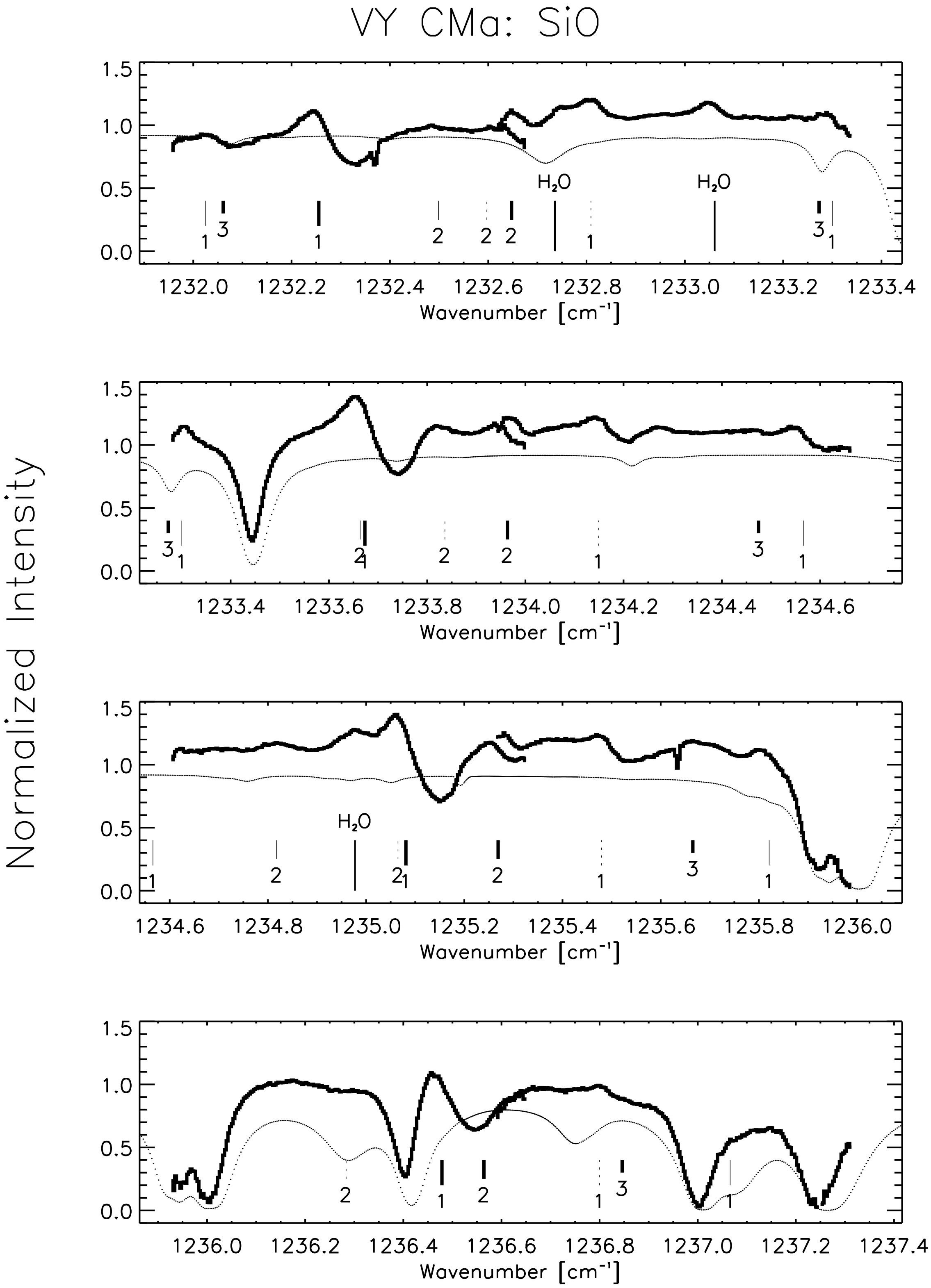

Fig. 1. An example of data obtained with TEXES. The heavy line is the data and the dotted line is a model of the terrestrial atmosphere. Each panel has two orders with some overlap region. SiO lines are identified by tick marks (adjusted for a velocity of 55 km s^{-1}) with the number of the upper vibrational state below the tick mark. The heavy, dotted, and thin ticks indicate ^{28}SiO, ^{29}SiO, and ^{30}SiO, respectively. There are also three H_2O features seen.

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4. SOFIA

While we have shown that TEXES is a working instrument for ground–based, high–resolution, MIR spectroscopy, SOFIA will provide an exciting platform for using EXES. SOFIA, a collaborative effort between the US and Germany, consists of a 2.5 m aperture telescope in a Boeing 747 airplane. It will fly at altitudes up to 45,000 feet (13.5 km), above almost all of the terrestrial H_2O. Since H_2O is the dominant absorber over much of the infrared spectral region, SOFIA will be an outstanding platform for observations from 1 μm to 1 mm. SOFIA will have a suite of instruments covering a broad range of wavelength and spectral resolution and available to the entire astronomical community. Given the size of the telescope and the corresponding size of the instruments, SOFIA will provide unparalleled spatial and spectral resolution throughout much of the infrared spectrum. For more information regarding SOFIA, visit *http://sofia.arc.nasa.gov*.

When EXES flies on SOFIA, the superior atmospheric transmission from the stratosphere will significantly improve observations of many molecular species. For example, although certain pure rotational H_2 lines are accessible from the ground, SOFIA will permit observations of the ground state transition at 28.22 μm as well as the S(5) line at 6.91 μm; lines that are completely unavailable from the ground. H_2O is another molecule that will benefit from SOFIA. Based on ISO observations of H_2O absorption toward AFGL 2591 (Helmich et al. 1996), we believe we can determine the temperature and column of the absorbing molecules from a single wavelength setting. Because of our point source sensitivity, EXES will be able to probe numerous lines–of–sight.

5. CONCLUSIONS

We currently have a working high–resolution, MIR spectrograph for ground–based observations, TEXES, and are designing a similar instrument, EXES, for SOFIA. Both instruments will be available to the general astronomical community for collaborative investigations. With a resolution of 3 km s^{-1} at 10 μm, we believe these instruments will be ideally suited for observations of molecular line strengths and kinematics in a wide range of objects: quiescent clouds, protostellar and protoplanetary disks, planetary atmospheres, and evolved stars.

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