

PRECISE LABORATORY MEASUREMENT OF LINE FREQUENCIES USEFUL TO  
STUDIES OF STAR AND PLANET FORMATION

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## PRECISE LABORATORY MEASUREMENT OF LINE FREQUENCIES USEFUL TO STUDIES OF STAR AND PLANET FORMATION

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In March 2002, we began a program in laboratory spectroscopy to provide accurate molecular line frequencies essential to studies of the motions and abundances in star-forming dense cores and planet-forming circumstellar disks. Summarized here is the progress that has been made in Year 3 of this grant.

### SiO

SiO is a well-known tracer of shock chemistry arising from protostellar outflows. Very narrow and fairly bright lines of SiO in the ground vibrational state have been observed in regions where protostellar outflows interact with the cold ambient gas [Lefloch et al., *Astrophys. J. Lett.* **504**, L109 (1998)]. In support of the astronomical observations in these regions, 10 successive rotational lines in the ground vibrational state of SiO between 86 and 500 GHz, and two lines near 800 GHz were measured in the laboratory to an accuracy of a few kHz. When our measurements are combined with a very precise measurement of the lowest (1 - 0) transition observed in a supersonic molecular beam by Fourier transform microwave (FTM) spectroscopy [Sanz et al., *J. Chem. Phys.* **119**, 11715 (2003)], the entire rotational spectrum is predicted to an accuracy of about 3 parts in  $10^8$  near 1,000 GHz. A manuscript providing a full account of this work is about to be submitted for publication in the *Astrophysical Journal*.

### MOLECULAR IONS $N_2H^+$ , $HCO^+$ , AND $H_2D^+$

Collision-induced frequency shifts are the largest source of uncertainty in the rotational line frequencies of molecular ions observed in the laboratory. In collaboration with Professor R. W. Field's group at MIT, we have been conducting pilot experiments on molecular ions in collision-free supersonic beams. If we succeed in observing the molecular ions  $HCO^+$ ,  $N_2H^+$ , and  $H_2D^+$  in supersonic molecular beams with sufficient sensitivity at millimeter and submillimeter wavelengths, then it will be feasible to determine accurate line frequencies. The SAO spectroscopy laboratory has enough equipment and expertise to conduct these measurements in-house, but it has proven more efficient to undertake the pilot experiments in Professor Field's laboratory. We should know within the next month whether precise line frequencies of molecular ions can be determined in these experiments. If the pilot experiments are successful, we then plan to measure accurate line frequencies of  $N_2H^+$ ,  $HCO^+$ , and  $H_2D^+$  in the SAO spectroscopy laboratory.

## CN AND CCH

The CN and CCH radicals are among the most important tracers of dynamical motions in protoplanetary disks around low mass pre-main sequence stars. The millimeter-wave spectrum of CN consists of rotational transitions every 113 GHz which are split into many resolved hyperfine components. Most of the leading spectroscopic constants are largely derived from the fundamental (1-0) transition, however the prior laboratory measurement of this transition by Claude Woods and coworkers in 1977 is not very accurate. We have now measured 22 lines of CN between 113 and 340 GHz. The uncertainties in the line frequencies calculated with our newly determined set of spectroscopic constants are 4 – 10 times smaller than those calculated with constants derived from previous work and are sufficiently precise (i.e., accurate to 4 parts in  $10^8$  or better) for astronomers studying dynamical motions in protoplanetary disks. The millimeter-wave spectrum of CCH is based on not very precise measurements made in this laboratory more than 20 years ago. We are in the process of remeasuring lines of CCH below 400 GHz and obtaining a much more precise set of line frequencies in the millimeter-wave band. A manuscript describing a full account of this work on CN and CCH is in preparation.

### SUB-DOPPLER MEASUREMENTS OF CCH, $C_3H_2$ , CCS, $H_2CS$ , AND SO

We have been setting up an experiment that would allow us to refine earlier measurements of the neutral species such as  $C_3H_2$ , CCS,  $H_2CS$ , and SO by observing the very narrow sub-Doppler (Lamb dip) features in the millimeter-wave spectra of these species. Until now, line frequencies of molecules produced in discharges were always obtained from fairly broad Doppler-limited line profiles, but it should be feasible to observe the sub-Doppler component in species such as these and thereby improve the measurement precision substantially. We have succeeded in observing the Lamb dip component in CS and are about to try to extend this technique to  $C_3H_2$ , CCS,  $H_2CS$ , SO, and other neutral species that are used as tracers of small dynamical motions in space.