The Renaissance of Submillimeter Astronomical Spectroscopy

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Abstract**—** High resolution spectroscopy is recognized as a powerful astrophysical tool. For understanding many critical aspects of the formation and evolution of interstellar clouds and how new stars are formed within them, the most important spectral lines are at submillimeter wavelengths, corresponding to the terahertz frequency range between 300 and 6000 GHz, (0.3 to 6 THz). In many astronomical situations, line widths resulting from Doppler shifts arising from gas motions can be $\leq$ 1 km/s. Thus, extracting the full information available about the kinematics of gas in the source being observed requires resolution $R = f/\Delta f \geq 3 \times 10^5$. This requires a heterodyne system, which can readily achieve the required frequency resolution. Exploiting the wealth of ionic, atomic, and molecular transitions has been hampered by the nearly total absorption by the Earth's atmosphere and the relatively low sensitivity of available detectors.

The situation has improved dramatically over the last decade. The development of the Heterodyne Instrument for Far Infrared (HIFI), on board the Herschel Space Observatory launched in 2009 encouraged a continuing technological transformation that includes vastly improved mixers, local oscillators, optics, and the development of focal plane arrays. The data from Herschel have inspired improved laboratory measurements generating spectral line catalogs, quantum calculations, and measurements of collision rates and chemical reaction rates for key astrophysical species. New observing platforms including the SOFIA airborne observatory and long-duration balloons flying at 40 km altitude have resulted in a stream of data of ever-increasing frequency coverage and range and extent of sources observed. Anticipated ultra-long-duration balloons and the possibility of space missions ranging from small satellites to a large-aperture major (Flagship) mission are generating great excitement about possible future observations.

In this talk I will review how the overall picture has evolved in recent years. I will highlight recent astronomical results, including velocity-resolved large-area studies of Giant Molecular Clouds and nearby galaxies in the 158 micron fine structure transition ([CII]) of C^+, high-sensitivity observation of water in collapsing cloud cores, and multi-transition observations of the CO ladder through the entire submillimeter range. I will indicate some of the most exciting areas for further exploitation in the years ahead, in these and other transitions including HD at 112 microns and the fine structure transitions ([NII]) of N^+ at 205 microns and 122 microns wavelength. The formation of new stars, particularly massive stars, is a key aspect of the evolution of galaxies, and understanding how new stars form requires observation of many different spectral lines that probe the physical conditions and chemical composition of interstellar clouds, including those regions that are actually collapsing to form a single protostar or a cluster of protostars.