observations of the radio property of granulation patterns, dark and bright mottles, oscillatory motions, plasma nodules, and magnetic field configurations in active and quiet regions. Thus the major goal of the future instrumentation will be to provide the resolution needed to relate radio and optical structure in order to identify the physical processes controlling solar emission.

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# Molecular Millimeter Wave Astronomy

LEWIS E. SNYDER

***Abstract*—Molecular millimeter wave astronomy is briefly reviewed. Particular emphasis is placed on the newer areas of research in astronomy and astrophysics which have been facilitated by radio observations of galactic molecules in the millimeter wavelength range of the spectrum.**

Manuscript received May 2, 1974. This work was supported in part by the National Science Foundation under Grant GP-34200.
The author is with the Joint Institute for Laboratory Astrophysics, University of Colorado and the National Bureau of Standards, Boulder, Colo. 80302, on leave from the Department of Astronomy, University of Virginia, Charlottesville, Va. 22903.

## INTRODUCTION

Four years ago, the detection of interstellar carbon monoxide [1] marked the beginning of millimeter wave molecular astronomy. At present, 33 species of interstellar molecules have been detected in our galaxy; of these only 4, CH, $CH^+$, CN, and $H_2$, were detected initially by optical and ultraviolet astronomers and only 2, $CH^+$ and $H_2$, are observed exclusively outside of the radio spectrum. Hence radio astronomers can observe 31 of 33 species of interstellar molecules. Nineteen of 30 have been observed only in the millimeter wavelength region (wavelengths of 1 mm and shorter) of the radio spectrum. Eight of 19 do not yet have firm molecular identifications. From another point of view, radio astronomers have reported 166 lines from 31 galactic molecules of which 107 were detected in the millimeter wavelength region. Most of the galactic molecular species and their detected lines have been listed elsewhere [2]–[4]. In this short paper, the areas of investigation which rely primarily on millimeter wave observations will be summarized.

## STRUCTURE OF INTERSTELLAR CLOUDS

The high spatial resolution of modern millimeter wave telescopes is the main reason that cloud mapping currently is the most active area of observational radio research. Typically, the brightness temperature or equivalent width from a given molecular transition is measured in numerous adjoining regions of a molecular cloud. The resulting data are plotted as a function of suitable astronomical coordinates, usually right ascension and declination, to make a two dimensional spatial map of the cloud. Maps from different molecular species in the same cloud may be compared to determine the extent of the gas cloud and often its velocity structure. As a final step, equations of radiative transfer are applied to obtain realistic evaluations of various physical properties such as gas kinetic temperature, density, and cloud mass. As one example, data from a recent carbon monoxide mapping program have been used to determine that the total mass of molecular hydrogen in L1630, a diffuse dark cloud, constitutes a significant fraction of the total mass of stars and gas within the boundaries of the I Ori association [5]. Other mapping programs have been designed to search for molecular emission from clouds surrounding stars [6], [7]. In the future, promising stars will be used as background radiation sources for infrared, optical, and ultraviolet satellite studies of the interstellar gas.

In general, a long-range goal of all molecular mapping programs is to understand the process of star formation. It is generally believed that the molecular clouds may represent a previously ignored stage of stellar evolution: the clouds are born when matter (which may come from dying stars) gravitationally accretes and, in turn, the terminal point of cloud evolution may be high density knots or "protostars" which will become new stars. Hence cloud mapping is an important first step in the attempt to understand the obscure half of a very complete stellar evolutionary track.

## ASTROCHEMISTRY AND ABUNDANCE RATIOS

Numerous astrochemical formation mechanisms have been suggested for simple interstellar molecules such as two-body radiative association, inverse predissociation, ion–molecule reactions, and interstellar grain surface reactions. At this time the radio detections of new and complex molecular species, particularly in the millimeter wavelength range, are far ahead of all quantitative molecular formation theories. For instance, methylacetylene [8], a seven-atom molecule, and dimethyl ether [9], a nine-atom molecule, have been detected near 3-mm wavelength. Hence, astrochemistry has presented molecular formation problems which may require new approaches to chemical reaction theory [10].

The question of isotopic abundance ratios in the galactic gas clouds is thought to be closely related to the problem of molecular formation [11]. For instance, if interstellar carbon monoxide primarily forms in the gas phase, we might expect to measure carbon and oxygen isotopic abundance ratios which reflect those of the atoms in the ambient gas (possibly close to terrestrial) but if more complex species, such as hydrogen cyanide and formaldehyde, primarily form on interstellar grain surfaces, their isotopic abundance ratios may deviate significantly from terrestrial.

Observationally, it has been found that carbon monoxide [12] has $^{12}C$:$^{13}C$ and $O^{16}$:$O^{18}$ ratios very close to the terrestrial values of

89 and 499, respectively; carbon monosulfide [13] has $^{12}C:^{13}C$ and $^{32}S:^{34}S$ ratios close to terrestrial except for the galactic center region where the $^{12}C:^{13}C$ ratio may be only half the terrestrial value; formaldehyde [14] in the galactic center has a $^{12}C:^{13}C$ ratio which is probably only 20–50; and hydrogen cyanide [15] in Orion appears to have a $^{12}C:^{13}C$ ratio which is much lower than terrestrial. It is hoped that comparisons such as these will lead to a better understanding of the astrochemical formation mechanisms for interstellar molecules.

## FUNDAMENTAL SPECTROSCOPY

A quantitative understanding of the structure of short-lived unstable molecular species is very important for numerous areas of research ranging from the chemistry of reactions to stellar astronomy. However, many short-lived species are difficult to study in the laboratory because either they are quickly destroyed by wall collisions or they chemically recombine to form other species faster than microwave measurements can be made. On the other hand, the molecular collision times may be on the order of years in the low density interstellar clouds; hence the interstellar medium provides an ideal environment for fundamental spectroscopic measurements of short-lived unstable molecular species. This was demonstrated convincingly when observational data from the $N = 1–0$ transition of interstellar CN at 2.6 mm were used for the first direct determination of the CN hyperfine, $\rho$-doubling, and rotational constants [16] after previous laboratory attempts were unsuccessful. The accuracies of the CN molecular constants are comparable to laboratory measurements of more stable molecules.

The 8-mm wave lines which do not yet have firm molecular identifications (81.541 [17], 85.435 [8], 87.316, 87.328, 87.402, 87.407 [18], 89.189 ($X$-ogen) [19], and 90.665 ("HNC") [20] GHz) are potentially important to fundamental spectroscopy in a less obvious way. While some of these lines undoubtedly will be identified as obscure transitions of well-known stable molecules, it is expected that many will be found to belong to molecular species too unstable to be studied directly in the laboratory. Hence, as with CN, the fundamental constants of these unstable molecules probably will be determined from the observational data of millimeter wave astronomers.

## COMETARY SPECTROSCOPY

Within the past year the first radio observations of polyatomic molecules in a comet were made in the millimeter wavelength region when the 36-ft (11-m) radio telescope of the National Radio Astronomy Observatory was used to detect both methyl cyanide [21] at 2.7 mm and hydrogen cyanide [22] at 3.4-mm wavelength in comet Kohoutek (1937*f*). For years, optical astronomers have observed the spectra of simple molecules in passing comets; contemporary comet theory postulates an icy nucleus which contains trace amounts of complex (or parent) molecules which evaporate and fragment to form the simpler (or daughter) molecules observed at optical wavelengths. Now millimeter wave astronomy offers the opportunity to detect and study the parent molecules. It should be noted that some astronomers expect that studies of parent molecules in comets will solve the old problem of where comets were born [23]. The current belief is that either comets were formed in the vicinity of Jupiter by condensing from the solar nebula or they originally were formed in the outer regions of (or even beyond) the solar system.

## MILLIMETER WAVE MASERS

In December 1973, the first millimeter wave maser was detected near 3.48-mm wavelength in the direction of Orion [24]. The carrier of the maser emission spectrum was believed to be the $J = 2–1$ transition of silicon monoxide in its first vibrationally excited state, but due to an unusual Doppler pattern, this identification could not be confirmed solely on the basis of the 3.48-mm data. Subsequently, the $J = 3–2$ transition (near 2.32 mm) and the $J = 1–0$ transition (near 6.95-mm wavelength) of vibrationally excited silicon monoxide were detected in Orion and were found to have Doppler patterns matching the emission spectrum near 3.48 mm [25], [26]; thus the vibrationally excited silicon monoxide identification has been confirmed. At present, 13 galactic silicon monoxide maser sources have been detected at 3.48-mm wavelength and, in almost all cases, it has been found that the emission originates from the dusty shells associated with late $M$-type Mira or semiregular variable infrared stars [27]. It would be premature at this time to try to estimate the impact of millimeter wave silicon monoxide observations on stellar astronomy, but several research directions are beginning to materialize. Most of the silicon monoxide maser sources also display time-varying maser emission from water vapor at 1.35 cm and from hydroxyl at 18-cm wavelength. Thus it is expected that observations of the three detected transitions of vibrationally excited silicon monoxide at 6.95-, 3.48-, and 2.32-mm wavelength will help bridge the spectrum between centimeter wavelength radio astronomy and infrared astronomy and will be particularly useful for maser research on time variations of infrared stars with dusty envelopes. Furthermore, if the size of the Orion region supporting the silicon monoxide is comparable to that found for the water maser [28] (0".01), then the brightness temperature of the siliconr monoxide maser emission at 3.48 mm is on the order of $10^9$ K; this is expected to encourage development of line interferometers operating near 3-mm wavelength.

## CONCLUSION

In conclusion, molecular millimeter wave astronomy has yielded discoveries and observations which not only enhance the content of areas of traditional astronomy (e.g., stellar evolution, circumstellar composition, cometary physics) but also contribute to other research areas such as molecular spectroscopy and chemical reaction theory.

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