INTERSTELLAR MOLECULES IN STAR FORMING REGIONS

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We discuss some of the characteristics of interstellar molecules and their radiation, concentrating on the rotational transitions of molecules in the gas phase. An up-to-date (November 2000) list of interstellar, circumstellar and cometary molecules is presented.
The Berkeley-Illinois-Maryland-Association array of radio telescopes is described and some of the recent BIMA observations of molecular emission from selected star-forming regions is presented. These include evidence for collapse in W 49 A north, complex molecules coming off of grain surfaces in Sgr B2 north, images tracing the molecular emission in the energetic DR 21 bipolar outflow, and large velocity gradients in the CO emission associated with the neutral columns of the Eagle Nebula.

INTRODUCTION

Only a few molecules were known to exist in interstellar space when OH, the first interstellar molecule to be discovered by radio techniques, was observed in 1963 [22]. By the year 2000, over 120 molecules have been discovered with the most complex, $HC_{11}N$, having 13 atoms [2]. The molecules are found in clouds of cold gas and dust which are distributed throughout the Milky Way Galaxy. These clouds are huge; they can have masses up to a million times the mass of the Sun and diameters of 300 light years. Molecular clouds fragment into small clumps which collapse to form stars. The more massive stars ionize their surroundings and begin to disrupt the remaining molecular clouds. Because molecular clouds are opaque to "visible" light, infrared and radio telescopes are required to study the dramatic activity within them.

CHARACTERISTICS OF INTERSTELLAR MOLECULES AND THEIR RADIATION

Radiation from molecules arises from 3 main types of transitions: between electronic states, vibrational states, and rotational states. Electronic transitions require considerable energy (kinetic temperatures, T_K, in the thousands of K) to excite the levels and the emission occurs in the optical part of the spectrum. Vibrational transitions require less energy ($T_K \sim 300-1000$K) and the emission occurs in the infrared and far infrared. The simplest transitions which require the least energy ($T_K \sim 3$K to 300K) are the rotational transitions which occur in the radio at cm, mm and submm wavelengths. Details of the microwave spectroscopy of molecular radiation are given by Townes and Schawlow [21].

In a typical molecular cloud with 10^9 hydrogen molecules per cubic meter there are approximately 10,000 CO molecules. For other molecular species such as CS, HCN, H_2CO, there is about 1 molecule each. Molecules are comprised of simple atoms in more or less their cosmic abundance, H, C, O, N, Si, S [9, 11]. The time between collisions is from hours to several hundreds years. Therefore, in the gas phase, only two body, not three body reactions occur. Simple molecules (other than H_2) can form in the gas phase whereas H_2 and more complex molecules are presumed to form through chemical reactions on the surfaces of interstellar grains.

The first 4 molecules detected by radio telescopes were found at cm wavelengths – OH [22], NH_3 [4], H_2CO [19], H_2O [5]. Once the 36′ radio telescope of the National Radio Astronomy Observatory became operational at 3 mm, many more molecules were discovered and the number has grown to over 120 molecules. Table 1 shows the list of interstellar, circumstellar, and cometary molecules as of November 2000 [16]. Compared to terrestrial laboratories, conditions in interstellar space are essentially a vacuum near absolute zero K.

Because the mean free path for a molecule in a molecular cloud can be as small as the diameter of the earth or as large as the solar system, there are few interactions. Therefore, it is not unusual to find free radicals –

Table 1: A list of the 126 reported gas-phase interstellar, circumstellar and cometary molecules. This list was compiled by L. E. Snyder, November 2000

2	AlF	$AlCl$	C_2	CH	CH^+	CN
	CN^+	CO	CO^+	CP	CS	CSi
	H_2	HCl	HF	KCl	LiH	N_2^+
	NH	NO	NS	$NaCl$	OH	OH^+
	PN	S_2	SH	SO	SO^+	SiN
	SiO	SiS				
3	C_3	C_2H	C_2O	C_2S	CH_2	CO_2
	HCN	HCO	HCO^+	HCS^+	H_3^+	HOC^+
	H_2O	H_2S	HNC	HNO	$MgCN$	$MgNC$
	NH_2	N_2H^+	N_2O	$NaCN$	OCS	SO_2
	c-SiC_2					
4	c-C_3H	l-C_3H	C_3N	C_3O	C_3S	C_2H_2
	CH_3	$HCCN$	$HCNH^+$	$HNCO$	$HNCS$	$HOCO^+$
	H_2CO	H_2CN	H_2CS	H_3O^+	NH_3	SiC_3
5	C_5	C_4H	C_4Si	l-C_3H_2	c-C_3H_2	CH_2CN
	CH_4	HC_3N	HC_2NC	$HCOOH$	H_2CHN	H_2COH^+
	H_2C_2O	H_2NCN	HNC_3	SiH_4		
6	C_5H	C_2H_4	CH_3CN	CH_3NC	CH_3OH	CH_3SH
	HC_4H	HC_3NH^+	HC_3HO	$HCONH_2$	l-H_2C_4	C_5N
7	C_6H	CH_2CHCN	CH_3C_2H	HC_5N	$HCOCH_5$	NH_2CH_3
	c-C_2H_4O					
8	CH_2OHCHO	CH_3COOH	CH_3C_3N	$HCOOCH_3$	C_7H	HC_6H
	H_2C_6					
9	CH_3C_4H	CH_3CH_2CN	$(CH_3)_2O$	CH_3CH_2OH	HC_7N	C_8H
10	$(CH_3)_2CO$					
11	HC_9N					
13	$HC_{11}N$					

OH [22], molecular ions – HCO^+ [3], and long chains – $HC_{11}N$ [2] in molecular clouds. The pace of discovery has not slowed, the latest detection being the first sugar – glycolaldehyde [10].

RADIO TELESCOPES – THE BIMA ARRAY

Many of early discoveries were made with NRAO 36′ (11-m) telescope at a wavelength 3 mm. The early maps had a resolution of about 1 arcmin. During the 1980s, larger radio telescopes and mm-wave arrays were constructed. For example, the **B**erkeley-**I**llinois-**M**aryland-**A**ssociation (BIMA) array shown in Fig. 1 is a 10 antenna aperture synthesis telescope which operates at wavelengths of 3 mm and 1 mm [24]. The BIMA telescopes are 6.1 m in diameter yielding a FWHP beam of 100″ at 115 GHz (∼3 mm). The antennas may be located at various stations along an approximately T-shaped track to obtain angular resolutions between about 0″.4 and 14″ at 100 GHz. Nine of the 10 antennas have both 3 mm (70–116 GHz) and 1 mm (210–270 GHz) SiS receivers. The tenth (of older design) has a 3 mm Schottky diode receiver.

The interferometer is insensitive to the very largest scale features. However, there are several advantages of interferometers over single dishes for detecting and imaging molecular line emission. One can image at high resolution over a large field of view, separate out different velocity structures which would overlap at lower resolution, and can locate the source of the emission within the field of view.

Figure 1: The 10-element BIMA mm-wave array in Northern California

RECENT INVESTIGATIONS OF STAR-FORMING REGIONS WITH THE BIMA ARRAY

W 49 A north – inverse P-Cygni profiles and collapse?

Welch *et al.* [23] imaged W 49 A north in the J=1−0 transition of HCO^+ with the **B**erkeley-**I**llinois-**M**aryland-**A**ssociation (BIMA) array at a resolution of ∼7″ and found an inverse P Cygni-like profile toward H II region **G** which they interpreted as being due to collapse of the overall molecular envelope onto the inner ring of ultracompact H II regions of which **G** is the most prominent one. Dickel & Auer [6] modeled the radiative transfer for such a global inside-out collapse and found that such a collapse model could satisfactorily reproduce observations of both the J=1−0 and the J=3−2 transitions of HCO^+ toward the dominant H II region. More recently, Dickel *et al.* [7] observed the J=2−1 transition of CS towards W49 A north and found the same inverse P-Cygni profile. Fig. 2 shows the effect of degrading the resolution and how important high resolution is for detecting the absorption and hence an inverse P-Cygni profile.

Sgr B2 north – Site for Complex Molecules

One of the best sites to search for new molecules is the Galactic Center region Sgr B2. Many of the complex molecules recently discovered in Sgr B2 with the BIMA array, such as ethyl cyanide, acetic acid, and possibly glycine are confined to Sgr B2 north where stars have only begun to form [17, 13, 18]. Complex molecules are thought to form on grain surfaces and are released into the gas phase once a star forms and heats the surroundings [20]. There is a window of opportunity to find complex molecules in the gas phase which is after star-formation

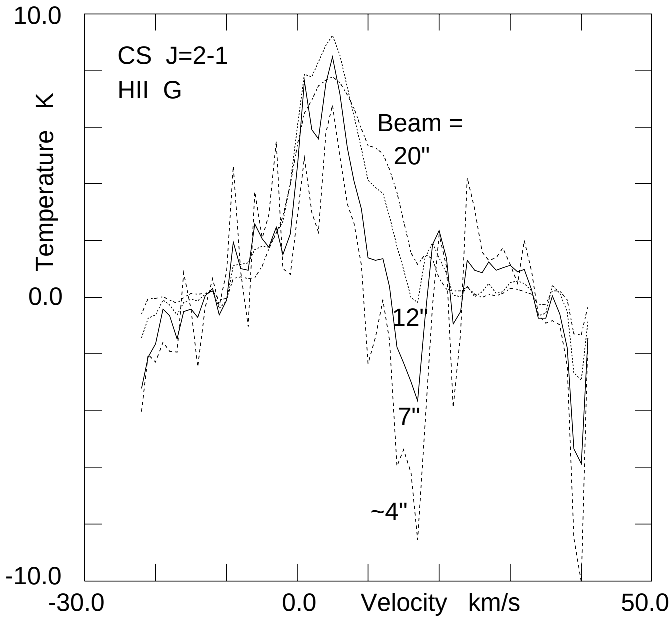

Figure 2: Effects of different resolutions on the observed inverse P-Cygni CS profile towards H II region G of W 49 A north

activity has released them from the grain surfaces but before they break apart and/or interact with other molecules.

DR 21 – Energetic Bipolar Outflows

A common phase of stellar evolution is the formation of large, bipolar outflows of molecular gas near young stellar objects [1]. One of the most massive and energetic outflows ($M > 3000\ M_\odot$, $E > 2\times10^{48}$ ergs) is found in the DR 21 star-forming region and has been imaged in HCO^+ with the BIMA array [8]. H I absorption against the continuum emission from the central H II regions shows an accelerating jet of H I gas originating between two of the exciting stars and extending out to the eastern HCO^+ lobe [15].

Eagle Nebula (M 16) – Disruption of Molecular Clouds

The Eagle Nebula (M 16) has been made famous by the beautiful images from the Hubble Space Telescope. Much of the material has been photoionized by nearby O stars. Columns of remaining dense neutral gas or "elephant trunks" are seen projected against the ionized gas. Around 70 "evaporating gaseous globules" (EGGS), small versions of the elephant trunks, have been uncovered as the columns are eroded away. Pound [14] imaged the Eagle Nebula in CO with the BIMA array. The CO emission is confined to the neutral columns where velocity gradients reach up to 20 km s^{-1} and point directly back to the O stars. These observations reveal the active destruction of a molecular cloud by the intense activity of nearby O stars.

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REFERENCES

[1] *Bally J., Lada C.* The high-velocity molecular flows near young stellar objects // Astrophys. J.–1983.–**265**, N 2.–P. 824–847.

[2] *Bell M., Feldman P., Travers M., et al.* Detection of $HC_{11}N$ in the cold dust cloud TMC-1 // Astrophys. J. Lett.–1997.–**483**, N 1.–P. L61–L64.

[3] *Buhl D., Snyder L.* Unidentified Interstellar Microwave Line // Nature.–1970.–**228**, N 5268.–P. 267–269.

[4] *Cheung A., Rank D., Townes C., et al.* NH_3 Molecules in the Interstellar Medium by their Microwave Emission // Phys. Rev. Lett.–1968.–**21**, N 25.–P. 1701–1705.

[5] *Cheung R. D., Townes C., Thornton D., Welch W.* Detection of Water in Interstellar Regions by it Microwave Radiation // Nature.–1969.–**221**, N 5181.–P. 626–628.

[6] *Dickel H., Auer L.* Modeling Radiative Transfer in Molecular Clouds I. HCO^+ in the Star-Forming Region W 49 A North // Astrophys. J.–1994.–**437**, N 1.–P. 222–238.

[7] *Dickel H., Williams J., Upham D., et al.* Measurements of the J=2−1 Lines of CS and $C^{18}O$ toward the Star−forming Region W49A North // Astrophys. J. Suppl. Ser.–1999.–**125**, N 2.–P. 413–426.

[8] *Garden R. P., Carlstrom J. E.* High-velocity HCO^+ emission associated with the DR 21 molecular outflow // Astrophys. J.–1992.–**392**, N 2.–P. 602–615.

[9] *Goldsmith F.* Molecular Clouds: An Overview // Interstellar Processes / Eds Hollenbach and Thronson.–Astrophys. and Space Sci. Lib.–1987.–**134**,–P. 51–70.

[10] *Hollis J., Lovas F., Jewell P.* Interstellar Glycolaldehyde: The First Sugar // Astrophys. J.–2000.-**-540**, N 2.–P. L107-L110.

[11] *Irvine W., Goldsmith P., Hjalmarson A.* Chemical Abundances in Molecular Clouds // Interstellar Processes / Eds Hollenbach and Thronson.–Astrophys. and Space Sci. Lib.–1987.–**134**.–P. 561–609.

[12] *Lovas F., Snyder L.* Table of Interstellar Molecules / Ed. Lide.–CRC Handbook of Chemistry and Physics.–2001.–**81**.–in press.

[13] *Mehringer D.. Snyder L., Miao Y., Lovas F.* Detection and Confirmation of Interstellar Acetic Acid // Astrophys. J.–1997.–**480**, N 1.–P. L71–L74.

[14] *Pound M.* Molecular Gas in the Eagle Nebula // Astrophys. J.–1998.–**493**, N 2.–P. L113–L116.

[15] *Roberts D. A., Dickel H. R., Goss W. M.* High Resolution HI Zeeman Absorption Observations of DR21 // Astrophys. J.–1997.–**476**, N 1.–P. 209–220.

[16] *Snyder L.* List of reported gas-phase interstellar, circumstellar, and cometary molecules // Priv. Communic.–2000.

[17] *Snyder L.* Detection of large interstellar molecules with radio interferometers // Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms / Ed. Hoover.–Proc. SPIE.–1997.–**3111**.–P. 296–304.

[18] *Snyder L.* The Search for Interstellar Glycine // Planetary and Interstellar Processes Relevant to the Origins of Life / Ed. Whittet.–Kluwer Acad. Publ., 1997.–P. 115.

[19] *Snyder L., Buhl D., Zuckerman B., Palmer P.* Microwave detection of interstellar formaldehyde // Phys. Rev. Lett.–1969.–**22**, N 13.–P. 679–681.

[20] *Tielens A., Allamandola L.* Composition, Structure and Chemistry of Interstellar Dust // Interstellar Processes / Eds Hollenbach and Thronson.–Astrophys. and Space Sci. Lib.–1987.–**134**.–P. 397–469.

[21] *Townes C., Schawlow A.* Microwave Spectroscopy.–Dover Publ. NY, 1975.

[22] *Weinreb S., Barrett A., Meeks M., Henry J.* Radio observations of OH in the interstellar medium // Nature.–1963.–**200**, N 4909.–P. 829–831.

[23] *Welch W., Dreher J., Jackson J., et al.* Star formation in W49A - Gravitational collapse of the molecular cloud core toward a ring of massive stars // Science.–1987.–**238**, N 4833.–P. 1550–1555.

[24] *Wright M. C. H., Lugten J., Urry L., et al.* The Berkeley-Illinois-Maryland-Association Millimeter Array // Publs Astron. Soc. Pacif.–1996.–**108**.–P. 93–103.