Astronomy and Chemistry unified by Molecular Spectroscopy

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The four fields of sciences — Astronomy, Physics, Chemistry, and Biology — initially developed as accumulation of knowledge in individual field, but as they matured, neighboring fields were found to be deeply related. The unified fields — Astrophysics, Chemical Physics, and Biochemistry — are now well developed. Our age is the age of unification of next nearest neighbors — Astronomy and Chemistry, and Physics and Biology.

Fraunhofer's serendipitous discovery of the solar spectrum in 1817 demonstrated that the Sun is composed of the same atoms as on the earth and initiated the unification of astronomy and chemistry now called Astrochemistry or molecular astrophysics. The discovery also initiated modern astrophysics and spectroscopy. Kirchoff interpreted the Fraunhofer spectrum and established the theory of spectroscopy in 1858 and this led to the development of quantum mechanics. Spectroscopy developed from astronomical observations [1].

Subsequent more direct milestones of astrochemistry was the identifications of the spectra of interstellar diatomic molecules CH, CN[2], and CH^+ [3] in the early 1940s and discovery of microwave emission of interstellar NH_3 [4] and H_2O [5]; the latter caused an avalanche of discoveries of molecules, radicals and ions demonstrating rich chemistry in interstellar space.

By now astronomy — the science of stars, galaxies, and the Universe — and chemistry — the science of atoms, molecules, and matter — are deeply related in two fundamental ways. First, nuclei of atoms like C, N, O, etc. which make chemistry so rich are produced in the cores of stars, the only place with sufficiently high temperature and density required for nuclear fusion. The natural abundances of elements which govern chemistry is explained as results of nuclear astrophysics through the evolution of stars.

Second, stars are born in molecular clouds and the efficient heat disposal by molecular rotational emission is essential for continuous gravitational condensation of the gas and hence for star formation. Stars and molecules are like chicken and eggs; without stars, there wouldn't be molecules and without molecules, there wouldn't be stars [6].

I decided to spend my life for astrochemistry on December 17, 1968 [7] when I read Townes' paper on the discovery of interstellar NH_3 [4]. The discovery demonstrated surprisingly rich chemistry in interstellar space and introduced the new astronomical concept, *the molecular cloud*, with its unexpected high density. With participation of many active groups the field moved very quickly from the centimeter microwave region to the millimeter region.

My first observational success was discoveries in the centimeter region of long carbon chain molecules, HC_5N [8], HC_7N [9], and HC_9N [10] from 1975-1978. Forty years later, HC_9N is still the heaviest molecule observed by radio-astronomy. Harry Kroto, who supplied the laboratory data got obsessed on carbon chain molecules and sought for larger carbon chain molecules using Smalley's apparatus and serendipitously discovered C_{60} [11].

In 1970 a mysterious millimeter wave emission was discovered and named X-ogen [12]. Klemperer immediately speculated correctly [13] that its carrier is HCO^+, protonated CO, and this was the first observation ever of protonated ion in spectroscopy. This led to the idea that ion-neutral reactions which proceed efficiently independent of temperature are the key reactions to produce interstellar molecules [14] [15]. In their model calculations, particularly in Watson's [15], protonated molecular hydrogen, H_3^+ was singled out as playing the central role of universal proton donor (acid) thus initiating many chain reactions.

In October 1975, I started the search for the infrared spectrum of H_3^+ needed for its detection in interstellar space. The modern non-linear optical technique of difference frequency generation was chosen as the frequency tunable radiation source and the spectrum was detected in 1980 [16]. Helped by the invention of the velocity modulation method by Saykally [17], this led to an avalanche of laboratory infrared spectra of molecular ions. Amano [18] added many large protonated ions with his hollow cathode discharge. Infrared spectra of OH^+, OH^-, H_2O^+, H_3O^+, NH^+, NH_2^+, NH_3^+, NH_4^+, NH^-, NH_2^-, CH_2^+, CH_3^+, CH_5^+, CO^+, NO^+, C_2^-, HCO^+, HOC^+, HN_2^+, $HCNH^+$, $HCCH^+$, $HCCH_2^+$, H_2COH^+, CH_3CNH^+, $HOCO^+$, $HONN^+$, CO_2^+, CNC^+, N_3^-, NCO^-, $HCCCNH^+$, $HNCCN^+$ have been observed and a great many more if we list ions composed of atoms other than H, C, N, and O [19].

The search for interstellar H_3^+ was immediately started after the submission of [16] but it took 16 years till its detection in dense clouds [20]. Once detected, however, it was observed everywhere including diffuse clouds. Most surprisingly the H_3^+ number density was found to be nearly million times higher near the Galactic center [21] than the average in the Galaxy. Extensive observations have been conducted since and the results will be soon submitted [22].

On a separate front, the 100-years-old mystery of the Diffuse Interstellar Bands is beginning to be solved by the recent laboratory observation of the spectrum of C_{60}^+ by Maier [23]. The interdisciplinary field of Astrochemistry is in its most inspiring stage of progress.

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