Chemistry of the Universe

Participating Organizations
Emory University
The Ohio State University
Harvard-Smithsonian Center for Astrophysics
National Institute of Standards and Technology
National Radio Astronomy Observatory
University of Colorado
University of Virginia
University of Wisconsin

Mission Statement:
Combine the powerful tools of chemistry with the new capabilities of next-generation radio astronomy observatories to achieve a quantitative and predictive understanding of interstellar chemistry and make chemistry a primary tool for exploring the structure and evolution of the Universe.

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Origins of Nanoscience:
Exotic Molecules and Chemistry in Space

The role of basic science in creating new research frontiers
Essential Results from the Field of Interstellar Chemistry

• Space is not empty

• The basic chemistry of life emerges under inhospitable conditions

• We know about this chemistry through quantitative measurement

• Chemistry is Universal
Space is Not Empty

- Nature’s largest reservoirs of molecular material are found in the space between the stars

The Interstellar Hockey Stick
Detection of Water in Interstellar Regions by its Microwave Radiation

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A report of the detection of microwave radiation from water molecules in space, by the group which recently detected interstellar ammonia emission.

Fig. 2. Observed spectral intensity of $J_{19} = 6_{18} - 5_{23}$ H$_2$O rotational transition in the direction of the Orion Nebula. The position of peak emission is $\alpha_{1950.0} = 5^h 32^m 57^s \pm 4^s$, $\delta_{1950.0} = -5^\circ 25' 5'' \pm 1'.0$. 

[Graph showing the spectral intensity with a peak at a specific velocity]
Images of Orion

Notable Recent Findings: Water on Mars (Phoenix) Water on the Moon

Credit: Mouser Williams Wikipedia

http://www.spitzer.caltech.edu
The Basic Chemistry of Life Emerges from the Cold and the Dust

Orion Horsehead Nebula
http://www.eso.org/public/images/eso0202b/

Organic Chemistry at 100K
The Life Cycle of Molecular Material

**DENSE CLOUD**
The mass of an interstellar cloud becomes sufficient to cause contraction by self-gravitation, leading to the formation of protostellar systems. In this phase, complex prebiotic molecules form that can be detected by the GBT.

**DIFFUSE CLOUD**
The material blown off from many stars accumulates to form an interstellar cloud of gas and dust of very low density. In such clouds, simple molecules form that can be detected with the GBT.

**ACCRETION DISK**
A protostellar system further contracts, forming a central protostar and a rotating disk of gas and dust that accretes more material. More molecules form. Planets and comets eventually will form from the material in the outer disk.

**MASS LOSS**
As the star's nuclear fuels deplete, the star becomes unstable, and blows off mass. In this process, more molecules are formed that can be detected by the GBT. The material is ejected into the interstellar medium.

** STELLAR SYSTEM**
The central temperature and density increase, igniting thermonuclear reactions in the central star. Radiation from this newborn star drives the remaining gas and dust from the system. Planets, comets, and interplanetary material remain in orbit around the star.

**ZOOM TO PLANET**
The prebiotic molecules are delivered to planets by passing comets, interplanetary dust particles, and meteorites.
The Role of Quantitative Measurement in Interstellar Chemistry

We have a high certainty of the identity of interstellar molecules through their unique quantum mechanical spectra.

Rotational Spectroscopy as a Molecular Fingerprint

Frequency Measures Shape
Blackbody Radiation Curves (Continuum Emission)

Next Generation NRAO Telescope Facilities:
ALMA: 30 GHz (1 cm) – 1 THz (0.3mm)
EVLA: 2 GHz (15 cm) – 50 GHz (0.6 cm)
Radio Astronomy Tools for Molecular Detection

Single Dish Radio Telescopes: Green Bank Telescope 100m: Microwave (~50 GHz)
Single Dish Telescopes Provide Spectra

PRIMOS Survey Scan with the Green Bank Telescope

Sagittarius B2 N (SgrB2 (N))

Pure Rotational Spectrum of Methanol

PRIMOS Survey with the GBT
Laboratory Spectrum (CP-FTMW)

- $^9_{19} - ^8_{27} E$
  - 9936.20 MHz
- $^4_{32} - ^5_{23} A$
  - 9978.87 MHz
- $^4_{31} - ^5_{24} A$
  - 10058.27 MHz

Frequency (MHz)
Images in Astronomy

http://hubblesite.org/newscenter/archive/releases/2004/07/image/a/warn/
Radio Astronomy Tools for Molecular Imaging

*The Era of Broadband Interferometers*

(NRAO)

ALMA
Atacama Desert, Chile

September 28, 2010

www.almaobservatory.org
Unusual Carbon Chemistry of the Interstellar Medium

Types of Carbon Bonds:

- **sp-hybridized (linear)** (acetylene)
- **sp\(^2\)-hybridized (planar)** (ethene)
- **sp\(^3\)-hybridized (tetrahedral)** (ethane)
In terrestrial chemistry, “saturated” carbon species dominate ($C_{N}H_{2N}$):

\[ \text{CH}_4 \text{ (methane)} \quad \text{C}_4\text{H}_{10} \text{ (butane)} \quad \text{C}_8\text{H}_{18} \text{ (octane)} \]

In space, a “carbon rich” chemistry was common:

\[ \text{HC}_9\text{N} \]

($\text{HC}_{11}\text{N}: 1997$)

McCall B J Phil. Trans. R. Soc. A 2006;364:2953-2963
New Forms of Carbon

An Inspiration from Studying the Chemistry of Space

\[ C_{60}: \text{Buckminsterfullerene} \]


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During experiments aimed at understanding the mechanisms by which long-chain carbon molecules are formed in interstellar space and circumstellar shells\(^1\), graphite has been vaporized by laser irradiation, producing a remarkably stable cluster consisting of 60 carbon atoms. Concerning the question of what kind of 60-carbon atom structure might give rise to a superstable species, we suggest a truncated icosahedron, a polygon with 60 vertices and 32 faces, 12 of which are pentagonal and 20 hexagonal. This object is commonly encountered as the football shown in Fig. 1. The \( C_{60} \) molecule which results when a carbon atom is placed at each vertex of this structure has all valences satisfied by two single bonds and one double bond, has many resonance structures, and appears to be aromatic.

Fig. 1 A football (in the United States, a soccer ball) on Texas grass. The \( C_{60} \) molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.
The rise of graphene

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Figure 1: Mother of all graphitic forms. Graphene is a 2D building material for carbon materials of all other dimensions. It can be wrapped up into 0D buckyballs, rolled into 1D nanotubes or stacked into 3D graphite.

Nobel Prize in Physics 2010
25 Years of C$_{60}$

The discovery of buckminsterfullerene has had a widespread impact throughout science.

C$_{60}$ was the first of a series of new carbon nanomaterials

Detection of C$_{60}$ and C$_{70}$ in a Young Planetary Nebula

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In recent decades, a number of molecules and diverse dust features have been identified by astronomical observations in various environments. Most of the dust that determines the physical and chemical characteristics of the interstellar medium is formed in the outflows of asymptotic giant branch stars and is further processed when these objects become planetary nebulae. We studied the environment of Tc 1, a peculiar planetary nebula whose infrared spectrum shows emission from cold and neutral C$_{60}$ and C$_{70}$. The two molecules amount to a few percent of the available cosmic carbon in this region. This finding indicates that if the conditions are right, fullerenes can and do form efficiently in space.
NSF Centers for Chemical Innovation

Chemistry of the Universe

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The Ohio State University
Harvard-Smithsonian Center for Astrophysics
National Institute of Standards and Technology
National Radio Astronomy Observatory
University of Colorado
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