

Ge/Ch 128 - Cosmochemistry (3-0-6)

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Class Time: T.B.D.; organizational meeting 3/28/2005, 9:30 am 162 S. Mudd.

Description:

This course will examine the chemistry of the interstellar medium, of protostellar nebulae, and of primitive solar system objects with a view towards establishing the chemical evolution of atoms in the interstellar radiation field to complex molecules and aggregates in the early solar system. Emphasis will be placed on identifying the physical conditions in various objects, time scales for physical and chemical change, chemical processes leading to change, observational constraints, and various models which attempt to describe the chemical state and history of cosmological objects in general and the early solar system in particular.

Prerequisite : Instructor's permission. 3 lecture hours/week + bi-weekly problem sets. Midterm + final. No text required. Final will consist of a short oral presentation and written report.

Courses of related interest:

Ay122. Astronomical Measurements and Instrumentation. First term.

Ay126. Interstellar Medium. Second term.

Ch120. The Nature of the Chemical Bond. First, second, third terms.

Ch135. Chemical Dynamics. Third, second terms.

Ge131. Planetary Structure and Evolution. Third term.

Ge 133. The Formation, Evolution, and Detection of Planetary Systems. First term.

Ge140. Introduction to Isotope Geochemistry. Second term.

Ge232. Chemistry of the Solar System. Second term. Not offered in 2002-03.

Course Lecture Outline (Topics, not Lecture numbers)

I. Introduction to the cosmic environment

The four phases of the interstellar medium (ISM). Types of interstellar clouds with examples of physical conditions and time scales. Cloud structure and distance scales. Star formation, YSOs, and protostellar disks.

II. Introduction to interstellar molecules and dust

Galactic ecology, exchange of gas and dust between stars and the interstellar medium. Molecular survey: abundances by cloud type, observational techniques and examples, distributions and correlations. Interstellar grains and mantles: opacity laws, composition from UV, visible, IR spectroscopy, mantle formation and desorption, lifecycles of grains.

III. Molecule formation mechanisms

In situ synthesis required, so derive required formation rates in gas phase and on surfaces. Examine collision rates in ISM, show many processes too slow.

IV. Physics of chemical reactions

Derive ion-molecule reaction rate theory, compare with neutral/neutral chemistry and e^- /ion recombination. Energetics of reactions: potential energy surfaces, barriers, temperature dependence.

V. Types of chemical reactions

Positive ion reactions (radiative association, ion-molecule, condensation, charge transfer, etc.), negative ion reactions, neutral/neutral reactions (bimolecular, surface, atom-radical, etc.).

VI. The first gas-phase bond: H_2

Why gas phase methods usually fail. Grain surface binding, reactivity, ejection. Required formation rates and formation/destruction balance (photochemistry).

VII. Observational properties of diffuse clouds

Restatement of molecules present and physical conditions. Atomic abundances and ionization potentials, the Lyman limit. Photoionization rates, ionization equilibrium, and initial atom/ion abundances. Photodissociation with typical cross sections, example rates, types.

VIII. Bond formation and chemistry of key species in diffuse clouds

Primary mechanisms: radiative association, attachment, grains. O-H, C-H, N-H, C-O, C-C, and C-N bond formation. Chemistry of CO, OH, C_2 , and CN with density and photon flux, and CH^+ formation in shocks.

IX. Observational properties of dense clouds

Physical conditions and molecular abundances with example spectra, lifetimes, and correlations. The radiation field: ionization equilibrium, local UV, X-ray sources. Special cases: shocks, circumstellar shells, T-Tauri phases.

X. Chemical processes and timescales in dense clouds

Cosmic ray ionization, ion loss processes: reactions with H_2 , with O, and with other neutrals, recombination with e^- . Ionization equilibrium: H_3^+ to H/CO^+ conversion, metals, depletion, effects of grains.

XI. Major chemical cycles in dense clouds

C⁺-C-CO conversion sequence (observational and theoretical), review of C⁺ cycle, the C cycle. The CO chemical cycle: dependence on H₂O/OH, branching into hydrocarbon/organics channel. Organic pathways, reactions of CH₃⁺. The H₂O cycle and conflict with observations.

XII. Formation of complex molecules and chemistry of minor elements in dense clouds

Radiative association reactions (especially with CH₃⁺), formation of aldehydes, formates, etc. Carbon chains and rings. Other chains: C_n-CN, C_n-O, C_n-S, etc. Chemistry of Cl, S, Si, P.

XIII. Isotopes and isomers in the interstellar medium

Chemical fractionation: D, ¹³C, ¹⁵N, and ¹⁸O chemical fractionation reactions and temperature dependence. Photochemical fractionation: D/H fractionation of hydrocarbon clusters, D/H fractionation of small hydrides (water, methane) and temperature dependence. Isomer specific molecule formation in the ISM.

XIV. Interstellar dust

Formation in stellar winds, evolution of dust cores in ISM (timescales, depletions, destruction mechanisms, lifetimes). Processes on dust grains, size and compositional dependence. Formation and physics/chemistry of small carbonaceous grains.

XV. Icy grains and Grain Mantles

Formation of molecular grain mantles in clouds. Photophysical processing of grain mantles, depletion in dense clouds. Identification of interstellar grain mantles, IR spectroscopy. Organic refractory vs. metallic oxide grains.

XVI. Chemical models of the interstellar medium

Various types of chemical models (static, time dependent, dynamical, gas phase vs. surface, etc.) with successes and failures of each with comparison to observations. Diffuse cloud → dense cloud, dense cloud → protosolar nebula boundary conditions.

XVII. Physics of the solar nebula hypothesis #1

Theoretical models of star formation. The accretion disk paradigm. Estimates of the density, temperature profile in the pre-solar nebula. Mechanisms of angular momentum transfer in nebula.

XVIII. Physics of the solar nebula hypothesis #2

Planetesimal formation, accretion, timing and effects of stellar winds. Timescales for stellar and planetary formation. Observational constraints.

XIX. Introduction to solar nebula chemistry

Chemistry through the accretion shock, density increase. Compare/contrast kinetic timescales, thermodynamics. The equilibrium/condensation model, nebular thermochemistry.

XX. Detailed Equilibrium-Condensation Models and Thermochemistry

The equilibrium condensation sequence of various elements and minerals. Condensation products vs. oxygen/hydrogen fugacity. Volatile content of bodies with distance in pre-solar nebula.

XXI. Introduction to meteorites and interstellar dust particles

Classification of meteorite types, bulk abundances in meteorites and IDPs. Isotope ratios in and chemical properties of the major elements (H,C,N,O,Si,...) in meteorite classes. Residues

from meteoritical samples, concentrating on those with possible interstellar origins. Collection and analysis of interplanetary dust and its possible relation to the ISM.

XXII. Meteorites #2

Trace elements in meteorites, inclusions and isotope effects in small samples. Extinct radionuclides, fractionation problems, inclusions and the equilibrium/condensation model. Deduction of solar system formation time scales from isotope measurements.

XXIII. Origins of comets

The Oort cloud. Formation of cometary nuclei and creation of short vs. long period orbits. Non-orbital comets.

XXIV. Chemistry of comets

Cometary composition as a function of formation location. Chemistry in cometary comae and tails. The *Giotto* results from Comet Halley. Are comets “interstellar” or “nebular”?

XXV. Jovian planets and satellites

Formation scenarios for the Jovian planets and satellites. Timescales for planetary formation, kinetics vs. thermochemistry. Chemical evolution of Jovian atmospheres and satellite atmospheres. Isotope ratios in Jovian atmospheres. Titan.

XXVI. Formation of the terrestrial planets

Composition of the inner terrestrial planets and their relationship to meteoritical (chondritic) composition. Comparisons with equilibrium-condensation models. Safranov scenarios and the possible role of giant impacts in volatile partitioning.

XXVII. The early Earth

Accretion history of the Earth, impacts. Evolution of the volatile budget of the Earth, possible magma ocean. Buffering by magma of primitive atmosphere. Relation of very early Earth to present day abundances. Pre-biotic chemical evolution.

XXVIII. The Grand Picture

Overview of current best estimates of the connections between the interstellar medium and our solar system. Analysis of how much the previous chemical history of the galaxy determined the evolution of solar system bodies. Future directions of laboratory, observational and theoretical research.

Some Useful Reference Books for Ge/Ch 128: Cosmochemistry

Text Material in “Cosmochemistry” (most in Robinson Astrophysics Library):

- [1] *Interstellar Chemistry*, W.W. Duley and D.A. Williams (Academic Press, New York, 1984).
- [2] *Physical Processes in the Interstellar Medium*, L. Spitzer, Jr. (J. Wiley and Sons, New York, 1978).
- [3] *Interstellar Processes*, ed. D.J. Hollenbach and H.A. Thronson, Jr. (Reidel, Boston, 1987).
- [4] *Protostars and Planets III*, ed. E. Levy and J. Lunine (Univ. of Arizona Press, Tucson, 1993), *Protostars and Planets IV*, ed. V. Mannings, A. Boss, S. Russell (Univ. of Arizona Press, Tucson, 2000).
- [5] *Molecules in Astrophysics*, I.A.U. Symposium No. 178, ed Ewine F. van Dishoeck (Kluwer, Dordrecht, 1997).
- [6] *Herbig-Haro Flows and the Birth of Low Mass Stars*, I.A.U. Symposium No. 182, ed B. Reipurth and C. Bertout (Kluwer, Dordrecht, 1997).
- [7] *Physical Processes in Interstellar Clouds*, ed. G.E Morfill and M Scholer (Reidel, Boston, 1987).
- [8] *Interstellar Molecules*, I.A.U. Symposium No. 8, ed B. Andrews (Reidel, Boston, 1980).
- [9] *Molecular Astrophysics*, ed G.H.F. Dierksen, W.F. Huebner, and P.W. Langhoff (Reidel, Boston, 1985).
- [10] *Rate Coefficients in Astrochemistry*, ed. T.J. Millar and D. Williams (Kluwer, Dordrecht, 1988).
- [11] *Workshop on Laboratory and Observational IR Spectra of Interstellar Dust*, ed. R. Wolstencroft and M. Greenberg (Royal Observatory of Edinburgh, 1983).
- [12] *Polycyclic Aromatic Hydrocarbons and Astrophysics*, ed. A. Leger, L. d’Hendecourt, and N. Boccara (Reidel, Boston, 1987).
- [13] *Ices in the Solar System*, ed. J. Klinger, D. Bense, A. Dolfus, and R. Smoluchowski (Reidel, Boston, 1985).
- [14] *Comets*, ed. L.L. Wilkening, (Univ. of Arizona Press, Tucson, 1982).
- [15] *Physics and Chemistry of Comets*, ed. W.F. Huebner (Springer-Verlag, Berlin, 1990).
- [16] *Meteorites*, J.T. Wasson (W.H. Freeman and Co., New York, 1985).
- [17] *Meteorites and the Early Solar System*, ed. J.F. Kerridge and M.S. Matthews, (Univ. of Arizona Press, Tucson, 1988).

Useful Physics and Chemistry Texts:

- [1] *Collision Phenomena in Ionized Gases*, E.W. McDaniel (John Wiley and Sons, New York, 1964).
- [2] *Photochemistry of Small Molecules*, H. Okabe (John Wiley and Sons, New York, 1978).
- [3] *Photoionization Processes in Gases*, G.V. Marr (Academic Press, New York, 1967).
- [4] *Fundamental Processes in Radiation Chemistry*, ed. P. Ausloos (John Wiley and Sons, New York, 1968).
- [5] *Ion-Molecule Reactions*, E.W. McDaniel, V. Cermak, A. Dalgarno, E.E. Ferguson, and L. Friedman (John Wiley and Sons, New York, 1970).
- [6] *Gas Phase Ion Chemistry*, ed. M.T. Bowers, two volumes (Academic Press, New York, 1979).
- [7] *Structure/Reactivity and Thermochemistry of Ions*, ed P. Ausloos and S.G. Lias (Reidel, Boston, 1987).
- [8] *Chemical Kinetics*, R.E. Weston and H.A. Schwarz (Prentice-Hall, New York, 1972).

Older reviews and tutorials of "historial" interest:

- [1] "The Formation of Interstellar Molecules" E. Herbst and W. Klemperer *Physics Today* **29**, 32(1976).
- [2] "Physical Processes for the Formation and Destruction of Interstellar Molecules" W.D. Watson, *Atomic and Molecular Physics and the Interstellar Medium*, p. 181(North Holland, Amsterdam, 1975).
- [3] "Organic Molecules in Space" G. Winnewisser and E. Herbst, *Topics in Current Chemistry* **139**, 121(1987).
- [4] "Star Formation in Molecular Clouds: Observation and Theory" F.H. Shu, F.C. Adams, and S. Lizano, *Ann. Rev. Astron. Astrophys.* **25**, 23(1987).
- [5] "Recent Progress in Astrochemistry " B.E. Turner, *Space Science Reviews* **51**, 235(1989).