

DEPARTMENT OF PHYSICS AND ASTRONOMY  
UNIVERSITY OF MASSACHUSETTS

035152

NASA GRANT NAGW-436

BOUNDARY CONDITIONS FOR THE PALEOENVIRONMENT: CHEMICAL AND  
PHYSICAL PROCESSES IN THE PRE-SOLAR NEBULA

SUMMARY OF RESEARCH (FINAL REPORT)

February 15, 1983- June 30, 1997

Principal Investigator: William M. Irvine  
Co-Principal Investigator: F. Peter Schloerb

Summary:

The basic theme of this program is the study of molecular complexity and evolution in interstellar clouds and in primitive solar system objects. Research has included the detection and study of a number of new interstellar molecules and investigation of reaction pathways for astrochemistry from a comparison of theory and observed molecular abundances. The latter includes studies of cold, dark clouds in which ion-molecule chemistry should predominate, searches for the effects of interchange of material between the gas and solid phases in interstellar clouds, unbiased spectral surveys of particular sources, and systematic investigation of the interlinked chemistry and physics of dense interstellar clouds. In addition, the study of comets has allowed a comparison between the chemistry of such minimally thermally processed objects and that of interstellar clouds, shedding light on the evolution of the biogenic elements during the process of solar system formation.

Three PhD dissertations on this research were completed by graduate students at the University of Massachusetts. An additional 6 graduate students at the University of Massachusetts and 7 graduate students from other institutions participated in research supported by this grant. Six postdoctoral research associates worked on this grant, receiving valuable training.

### Recent Research (August 1996 - June 1997):

Graduate student J. Dickens, Principal Investigator W. Irvine, and colleagues in Japan and Sweden have identified a new cyclic molecule in interstellar clouds, ethylene oxide (c-C<sub>2</sub>H<sub>4</sub>O). Combining observations carried out at the NERO Haystack Observatory in Massachusetts with data from spectral surveys made at the Nobeyama Radio Observatory in Japan and the Swedish-European Submillimeter Telescope (SEST) in Chile, they have assigned 10 observed emission lines in the Galactic center cloud Sgr B2(N) to this molecule. Ethylene oxide is a higher energy isomer of the known interstellar molecule acetaldehyde (CH<sub>3</sub>CHO) and of the as yet undetected species vinyl alcohol (CH<sub>2</sub>CHOH). Ethylene oxide is an order of magnitude less abundant than acetaldehyde in Sgr B2(N), but the combined abundances of these isomers is at least a factor of 200 larger than the predictions of recent gas phase chemical models. This suggests that the production of these relatively large organic molecules involves grain-mediated processes, consistent with previous suggestions for species such as ethanol.

The current apparitions of Comet Hale-Bopp (C/1995 O1), the intrinsically brightest comet to be observable with contemporary instrumentation, and the very close-approaching Comet Hyakutake (C/1996 B2) have provided a spectacular opportunity to study cometary chemistry and physics. We have used the University of Massachusetts' Five College Radio Astronomy Observatory (FCRAO) to make regular maps of the emission from HCN, a presumed nuclear constituent, for both comets. For the more easily observable Comet Hale-Bopp we have mapped HCN, CS (a "daughter molecule", produced by photodissociation of a parent which may be CS<sub>2</sub>), and HCO<sup>+</sup>. The large extent of the emission from the latter ion, and its constantly changing morphology, manifest a previously unknown cometary phenomenon.

Observations of Comets Hyakutake and Hale-Bopp were also made in a collaborative program with astronomers from the University of Hawaii and the Joint Astronomy Centre, using the James Clerk Maxwell Telescope (JCMT) in Hawaii at submillimeter wavelengths. A principal goal of this research was to study the relationship of cometary to interstellar molecular matter, by searching for HNC, the

higher energy isomer of HCN. Under thermochemical equilibrium conditions there would be no HNC present in either environment. However, HNC is found to be relatively abundant in interstellar molecular clouds, a result that has traditionally been taken as strong supporting evidence for the validity of gas phase ion-molecule models for interstellar chemistry. Our detection of HNC in Comet Hyakutake (Irvine et al., Nature 383, 418, 1996) thus potentially provided a new chemical link between the solar system's parent molecular cloud and the solar nebula. There remains the possibility, however, that the observed cometary HNC may have been produced by photochemical processes after the comet entered the inner solar system, rather than being preserved interstellar material. In the former case the HNC/HCN abundance ratio would be expected to vary with the heliocentric distance of the comet. To investigate this phenomenon we have been making regular observations of both HNC and HCN throughout the apparition of Comet Hale-Bopp. Analysis of the data has begun.

Searches for additional molecules in the coma of Comet Hale-Bopp were made in order to study chemical composition and processes. Upper limits were obtained at various times during the apparition for  $\text{CH}_2\text{NH}$ ,  $\text{HC}_3\text{N}$ ,  $\text{CCS}$ ,  $\text{HC}_5\text{N}$  and  $\text{C}_3\text{H}_2$ , using FCRAO, the Haystack Observatory and the JCMT.

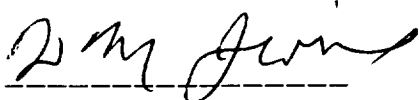
Our long-standing interest in the chemistry of regions which may become sites for solar-type star formation has stimulated the most thorough study ever attempted of the interlinked chemistry and physics of interstellar dark clouds. Two regions, Taurus Molecular Cloud One (TMC-1) and Lynds 134 North (L134N), were selected, since previous research suggested that they had similar physical properties (kinetic temperature and density) but differing compositions. Since determination of accurate molecular abundances requires knowledge of the physical conditions in the clouds, a large and diverse data set was obtained from which internally consistent values of both the physical conditions and the chemical abundances could be derived. Moreover, since the abundances are predicted to vary with the temperature and density, observations were made over extended regions of the sources to search for gradients in these physical parameters and in the corresponding chemistry. Emission from 34 rotational transitions of 22 molecular species and

isotopomers was mapped using the unique capabilities of the QUARRY focal plane array receiver on the FCRAO 14m telescope. The analysis of the results for TMC-1 is complete. Clear abundance gradients are present, which can be well matched by current models for a small variation in chemical timescales across the cloud. Such variations could easily result from slightly differing initial conditions or from a small density gradient, since the timescales depend on density.

As part of their continuing study of the interplay of gas phase and grain-surface processes in interstellar clouds, Dickens and Irvine have been investigating the hydrogenation of small organic molecules. Even when such hydrogenation is energetically allowed, there are often activation barriers which are difficult to overcome at the low temperatures and densities of the interstellar medium. Following a comparison of the relative abundances of HCN and  $\text{CH}_2\text{NH}$  in both quiescent clouds and warmer regions of active star formation, they carried out a survey for  $\text{CH}_3\text{NH}_2$  in both types of region. Unfortunately, only upper limits on the abundance of  $\text{CH}_3\text{NH}_2$  were obtained for all sources outside the Galactic Center.

Irvine completed a review on the nature and distribution of extraterrestrial organic matter, based on an invited talk presented at the 1996 ISSOL meeting in Orleans, France.

Irvine attended the Symposium "The Far Infrared and Submillimetre Universe", organized by the European Space Agency in connection with planning for the FIRST mission, and presented a paper on the  $\text{HCO}^+$  observations of Comet Hale-Bopp. Schloerb presented a paper on the HCN observations of Comet Hyakutake at the 1996 meeting of the AAS Division for Planetary Sciences. Irvine was an invited participant at the NASA Ames Astrobiology Workshop in September, 1996, and helped in the preparation of the final report (NASA Conf. Publ. 10153).



W. M. Irvine, PI



F. P. Schloerb, Co-PI

July 1, 1997

## VI. BIBLIOGRAPHY (PAPERS SUPPORTED BY GRANT NAGW-436)

### A. Research Papers:

1983 Irvine, W.M., J.C. Good, and F.P. Schloerb, "Observations of SO<sub>2</sub> and HCS<sup>+</sup> in Cold Molecular Clouds", *Astron. Astrophys.*, **127**, L10.

1984 Broten, N.W., J.M. Macleod, L.W. Avery, W.M. Irvine, B. Høglund, and Å. Hjalmarsen, "The Detection of Interstellar Methylcyanoacetylene", *Astrophys. J. (Lett.)*, **276**, L25.

1984 Irvine, W.M., and Å. Hjalmarsen, "The Chemical Composition of Interstellar Molecular Clouds", *Origins of Life*, **14**, 15 (Invited Review).

1984 Irvine, W.M. and F.P. Schloerb, "Cyanide and Isocyanide Abundances in the Cold, Dark Cloud TMC-1", *Astrophys. J.*, **282**, 516.

1984 Johansson, L.E.B., C. Andersson, J. Ellder, P. Friberg, Å. Hjalmarsen, B. Høglund, W.M. Irvine, H. Olofsson, and G. Rydbeck, "Spectral Scan of Orion A and IRC+10216 from 72 to 91 GHz", *Astron. Astrophys.*, **130**, 227.

1984 Matthews, H.E., W.M. Irvine, P. Friberg, R.D. Brown, and P.D. Godfrey, "A New Interstellar Molecule: Tricarbon Monoxide", *Nature*, **310**, 125.

1984 Schloerb, F.P. and R.L. Snell, "Large-scale Structure of Molecular Gas in Heiles Cloud 2: A Remarkable Rotating Ring", *Astrophys. J.*, **283**, 124.

1985 Brown, R.D., P.D. Godfrey, D.M. Cragg, E.H.N. Rice, W.M. Irvine, P. Friberg, H. Suzuki, M. Ohishi, N. Kaifu, M. Morimoto, "Tricarbon Monoxide in TMC-1", *Astrophys. J.*, **297**, 302.

1985 Goldsmith, P.F., R.L. Snell, F.P. Schloerb, and W.M. Irvine, "Search for Molecular Oxygen in Dense Interstellar Clouds", *Astrophys. J.*, **289**, 613.

1985 Irvine, W.M., F.P. Schloerb, Å. Hjalmarsen, and E. Herbst, "The Chemical State of Dense Interstellar Clouds", in *Protostars and Planets II*, ed. D. Black and H. Matthews, Univ. Arizona Press, pp. 579-620 (Invited Review).

1985 Johansson, L.E.B., C. Andersson, J. Ellder, P. Friberg, Å. Hjalmarsen, B. Høglund, W.M. Irvine, H. Olofsson, and G. Rydbeck, "The Spectra of Origin A and IRC+10216 between 72.2 and 91.1 GHz", *Astron. Astrophys. Suppl.*, **60**, 135.

1985 Matthews, H.E., P. Friberg, and W.M. Irvine, "The Detection of Acetaldehyde in Cold Dust Clouds", *Astrophys. J.*, **290**, 609.

1985 Matthews, H.E. and W.M. Irvine, "The Hydrocarbon Ring C<sub>3</sub>H<sub>2</sub> is Ubiquitous in the Galaxy", *Astrophys. J. (Lett.)*, **298**, L61.

1985 Suzuki, H., M. Ohishi, M. Morimoto, N. Kaifu, P. Friberg, W.M. Irvine, and H.E. Matthews, "Recent Observations of Interstellar Molecules in Nearby Cold, Dark Interstellar Clouds", in *The Search for Extraterrestrial Life: Recent Developments*, ed. M. Papagiannis, (D. Reidel), pp. 139-144.

1985 Thaddeus, P., C.A. Gottlieb, Å. Hjalmarsen, L.E.B. Johansson, W.M. Irvine, P. Friberg, and R.A. Linke, "Astronomical Detection of the C<sub>3</sub>H Radical", *Astrophys. J. (Lett.)*, **294**, L49.

1986 Friberg, P., W.M. Irvine, S.C. Madden, Å. Hjalmarsen, "Studies of Organic Molecules Containing Methyl Groups in Dark Clouds", *Astrochemistry (IAU Symp. 120)*, ed. M.S. Vardya and S.P. Tarafdar (D. Reidel), pp. 201-202.

1986 Goldsmith, P.F., W.M. Irvine, Å. Hjalmarsen, and J. Ellder, "Variations in the HCN/HNC Abundance Ratio in the Orion Molecular Cloud", *Astrophys. J.*, **310**, 383.

1986 Irvine, W.M., "The Chemistry of Cold, Dark Interstellar Clouds", *Astrochemistry (IAU Symp. 120)*, ed. M.S. Vardya and S.P. Tarafdar (D. Reidel), pp. 245-252 (Invited Review).

1986 Irvine, W.M. and Å. Hjalmarson, "Observational Astrochemistry", *Adv. Space Res.*, **6**, 227.

1986 Madden, S.C., W.M. Irvine, and H.E. Matthews, "Detections of  $^{13}\text{C}$ -Substituted  $\text{C}_3\text{H}_2$  in Astronomical Sources", *Astrophys. J. (Lett.)*, **300**, L79.

1986 Madden, S.C., W.M. Irvine, H.E. Matthews, R.D. Brown, and P.D. Godfrey, "Ammonia Masers Detected in Star-forming Regions", *Masers, Molecules, and Mass Outflows in Star-forming Regions*, ed. A. Haschick (NEROC Haystack Obs.), pp. 289-298.

1986 Madden, S.C., W.M. Irvine, H.E. Matthews, R.D. Brown, and P.D. Godfrey, "New Interstellar Masers in Nonmetastable Ammonia", *Astrophys. J. (Lett.)*, **300**, L79.

1986 Matthews, H.E. and W.M. Irvine, "Observations of the Hydrocarbon Ring  $\text{C}_3\text{H}_2$ ", *Masers, Molecules, and Mass Outflows in Star-forming Regions*, ed. A. Haschick (NEROC Haystack Obs.), pp. 1-8.

1986 Matthews, H.E., S.C. Madden, L.W. Avery, and W.M. Irvine, "The  $\text{C}_3\text{H}_2$   $2_{20}-2_{11}$  Transition: Absorption in Cold, Dark Clouds", *Astrophys. J. (Lett.)*, L69.

1986 Wootten, A., F. Boulanger, M. Bogey, F. Combes, P. Encrenaz, L.M. Ziurys, and M. Gerin, "A Search for Interstellar  $\text{H}_3\text{O}^+$ ", *Astron. Astrophys.*, **166**, L15.

1986 Ziurys, L.M. and B.E. Turner, "Detection of Vibrationally Excited HCN", *Astrophys. J. (Lett.)*, **300**, L19.

1986 Ziurys, L.M. and B.E. Turner, " $\text{HCNH}^+$ : A New Interstellar Molecular Ion", *Astrophys. J. (Lett.)*, **302**, L31.

1986 Ziurys, L.M. and B.E. Turner, "New Interstellar Detections: Implications for Shock Chemistry", *Astrochemistry (IAU Symp. 120)*, ed. M.S. Vardya and S.P. Tarafdar (D. Reidel), pp. 289-292.

1986 Ziurys, L.M. and B.E. Turner, "Vibrationally-excited HCN in Orion-KL and IRC+10216", *Molecules, Masers, and Mass Outflows in Star-forming Regions*, ed. A. Haschick (NEROC Haystack Obs.), pp. 23-29.

1987 Bell, M.B., J.K.G. Watson, P.S. Feldman, H.E. Matthews, S.C. Madden, and W.M. Irvine, "Deuterium Hyperfine Structure in Interstellar C<sub>3</sub>HD", *Chem. Phys. (Lett.)*, 588.

1987 Irvine, W.M., P.F. Goldsmith, and Å. Hjalmarson, "Chemical Abundances in Molecular Clouds" in *Interstellar Processes*, ed. D. Hollenbach and H. Thronson (Dordrecht: Reidel), pp. 561-609 (Invited Review).

1987 Matthews, H.E., J.M. Macleod, N.W. Broten, P. Friberg, and S.C. Madden, "Observations of OCS and a Search for OC<sub>3</sub>S in the Interstellar Medium", *Astrophys. J.*, **315**, 646.

1987 Moriarty-Schieven, G., R.L. Snell, S.E. Strom, F.P. Schloerb, K.M. Strom, and G.L. Grasdalen, "High Resolution Images of the L1551 Bipolar Outflow: Evidence for an Expanding Accelerated Shell", *Astrophys. J.*, **319**, 742.

1987 Schloerb, F.P., R.L. Snell, and P.R. Schwartz, "1300  $\mu$ m Continuum and C<sup>18</sup>O Line Mapping of the Giant Molecular Cloud Cores in Orion, W49 and W51", *Astrophys. J.*, **319**, 426 .

1987 Ziurys, L.M., "Detection of Interstellar PN: The First Phosphorus-bearing Species Observed in Molecular Clouds", *Astrophys. J. (Lett.)*, **321**, L81.

1987 Ziurys, L.M. and P. Friberg, "Observations of SiO toward OMC-1: A New Outflow Source 1.5' South of Orion-KL?", *Astrophys. J. (Lett.)*, **314**, L49.

1988 Bell, M.B., L.W. Avery, H.E. Matthews, P.A. Feldman, S.C. Madden, and W.M. Irvine, "A Study of C<sub>3</sub>HD in Cold Interstellar Clouds", *Astrophys. J.*, **326**, 924.



1988 Friberg, P., S.C. Madden, W.M. Irvine, and Å. Hjalmarson, "Methanol in Dark Clouds", *Astron. Astrophys.*, **195**, 281.

1988 Irvine, W.M., L.W. Avery, P. Friberg, H.E. Matthews, and L.M. Ziurys, "Newly Detected Molecules in Dense Interstellar Clouds", *Astro. Lett. Comm.*, **26**, 167 (Invited Review).

1988 Irvine, W.M., P. Friberg, Å. Hjalmarson, S.I. Ishikawa, N. Kaifu, K. Kawaguchi, S.C. Madden, H.E. Matthews, M. Ohishi, S. Saito, H. Suzuki, P. Thaddeus, B.E. Turner, S. Yamamoto and L.M. Ziurys, "Identification of the Interstellar Cyanomethyl Radical ( $\text{CH}_2\text{CN}$ ) in the Molecular Clouds TMC-1 and Sgr B2", *Astrophys. J. (Lett.)*, **334**, L107.

1988 Irvine, W.M., H.M. Matthews, P. Friberg, M. Ohishi, H. Suzuki, N. Kaifu, K. Kawaguchi and S.I. Ishikawa, "A New Interstellar Polyatomic Molecule: Detection of Propynal in the Cold Cloud TMC-1", *Astrophys. J.*, **335**, L89.

1988 Minh, Y., W.M. Irvine, and L.M. Ziurys, "Observations of Interstellar  $\text{HOCO}^+$ : Abundance Enhancements towards the Galactic Center", *Astrophys. J.*, **334**, 175.

1988 Minh, Y.C., W.M. Irvine, and L.M. Ziurys, " $\text{HOCO}^+$  Observations of Molecular Clouds", in *Molecular Clouds in the Milky Way and External Galaxies*, ed. R. Dickman, R. Snell, and J. Young (Berlin, Springer-Verlag), pp. 186-187.

1988 Saito, S., S. Yamamoto, M. Ohishi, H. Suzuki, W.M. Irvine, and L.M. Ziurys, "Laboratory Detection of a New Interstellar Free Radical  $\text{CH}_2\text{CN}$  ( $^2\text{B}_1$ )", *Astrophys. J. (Lett.)*, **334**, L113.

1988 Schenewerk, M.S., L.E. Snyder, J.M. Hollis, P.R. Jewell, and L.M. Ziurys, "HCO Emission from HII/Molecular Cloud Interfaces", *Astrophys. J.*, **328**, 785.

1988 Turner, B.E. and L.M. Ziurys, "Interstellar Molecules and Astrochemistry", in *Galactic and Extragalactic Radio Astronomy*, ed. K. Kellerman and G. Verschuur (Berlin, Springer-Verlag), pp. 200-254.

1988 Ziurys, L.M., "SiS in Orion-KL: Evidence for 'Outflow' Chemistry", *Astrophys. J.*, **324**, 544.

1988 Ziurys, L.M., N.R. Erickson, and R.M. Grosslein, "A Cooled 2mm Receiver for Radio Astronomy", in *Interstellar Matter*, ed. J. Moran and P.T.P. Ho (New York, Gordon & Breach), pp. 255-256.

1988 Ziurys, L.M., R.L. Snell, and R.L. Dickman, "Recent Molecular Studies of SNR IC443: Some New Results for Shock Chemistry", in *Molecular Clouds in the Milky Way and External Galaxies*, ed. R. Dickman, R. Snell, and J. Young (Berlin, Springer-Verlag), pp. 184-185.

1989 Irvine, W.M. and R.F. Knacke, "The Chemistry of Interstellar Gas and Grains", in *Origin and Evolution of Planetary Satellite Atmospheres*, ed. S.K. Atreya, J.P. Pollack, and M. Matthews (U. Arizona Press), pp. 1-34 (Invited Review).

1989 Irvine, W.M., Y.C. Minh, P. Friberg, H.E. Matthews, N. Kaifu, Y. Kitamura, N. Ukita, K. Kawaguchi, S. Saito, and S. Yamamoto, "Observations of Some Oxygen- and Sulfur-containing Organic Molecules in Cold, Dark Clouds", *Astrophys. J.*, **342**, 871.

1989 Irvine, W.M., "Observational Astrochemistry: Recent Results", *Adv. Space Res.*, **9**, (2)3 (Invited Review).

1989 Irvine, W.M., "Microwave Spectroscopy of Astrophysical Molecules", *Highlights of Astronomy*, **8**, 339 (Invited Review).

1989 Knacke, R.F., Y.H. Kim, and W.M. Irvine, "An Upper Limit to the Acetylene Abundance toward BN in the Orion Molecular Cloud", *Astrophys. J.*, **345**, 265.

1989 Madden, S., W.M. Irvine, H. Matthews, P. Friberg, and D. Swade, "A Survey for Cyclopropenylidene ( $C_3H_2$ ) in Galactic Sources", *Astron. J.*, **97**, 1403.

1989 Minh, Y.C., W.M. Irvine, and L.M. Ziurys, "Detection of Interstellar Hydrogen Sulfide in Cold, Dark Clouds", *Astrophys. J. (Lett.)*, **345**, L63.

1989 Ohishi, M., N. Kaifu, K. Kawaguchi, A. Murakami, S. Saito, S. Yamamoto, S. Ishikawa, Y. Fujita, Y. Shiratori, and W.M. Irvine, "Detection of a New Interstellar Carbon Chain Molecule, C<sub>4</sub>Si", *Astrophys. J. (Lett.)*, **345**, L83.

1989 Schwartz, P.R., R.L. Snell, and F.P. Schloerb, "1300  $\mu$ m Continuum and C<sup>18</sup>O Line Mapping of Giant Molecular Clouds II: W3, NGC2264, NGC6334I,  $\rho$  Oph, and S140", *Astrophys. J.*, **336**, 519.

1989 Ziurys, L.M., R. Snell, and R. Dickman, "Shock Chemistry in the Molecular Clouds Associated with SNR IC443", *Astrophys. J.*, **341**, 857.

1989 Ziurys, L.M., P. Friberg, and W.M. Irvine, "Interstellar SiO as a Tracer of High Temperature Chemistry", *Astrophys. J.*, **343**, 201.

1990 Irvine, W.M., S.C. Madden, L.M. Ziurys, P. Friberg, Å. Hjalmarsen, H.E. Matthews and B.E. Turner, "Observations of the CH<sub>2</sub>CN 1<sub>01</sub>-0<sub>00</sub> and 4<sub>04</sub>-3<sub>03</sub> Transitions", in *Submillimeter Astronomy*, ed. G.D. Watt and A.S. Webster (Kluwer), pp. 115-116.

1990 Irvine, W.M., P. Friberg, N. Kaifu, H.E. Matthews, Y.C. Minh, M. Ohishi, and S. Ishikawa, "Detection of Formic Acid in the Cold, Dark Cloud L134N", *Astron. Astrophys.*, **229**, L9.

1990 McGonagle, D., L.M. Ziurys, W.M. Irvine, and Y.C. Minh, "Detection of Nitric Acid in the Dark Cloud L134N", *Astrophys. J.*, **359**, 121.

1990 Minh, Y.C., L.M. Ziurys, D. McGonagle, and W.M. Irvine, "Observations of H<sub>2</sub>S towards OMC-1", *Astrophys. J.*, **360**, 136.

1990 Turner, B.E., P. Friberg, W.M. Irvine, S. Saito, and S. Yamamoto, "Interstellar Cyanomethane", *Astrophys. J.*, **355**, 546.

1990 Ziurys, L.M., "Millimeter and Submillimeter Studies of Interstellar High Temperature Chemistry", *Submillimeter Astronomy*, ed. G.D. Watt and A.S. Webster (Kluwer), pp. 109-110.

1991 Hollis, J.M., L.E. Snyder, L.M. Ziurys, and D. McGonagle, "Confirmation of the Identification of Interstellar HNO", in *Skylines: New Results in Spectral Line Astrophysics*, ed. A. Haschick and P.T.P. Ho, Astron. Soc. Pacific, Conf. Ser. **16**, 407.

1991 Irvine, W.M., "The Molecular Composition of Dense Interstellar Clouds", in *Chemistry in Space*, eds. J.M. Greenberg and V. Pirronello (Kluwer Academic Publishers), pp. 89-121 (Invited Review).

1991 Irvine, W.M., Å. Hjalmarsen and M. Ohishi, "Recent Developments in Interstellar Chemistry", in *Bioastronomy: The Exploration Broadens*, ed. J. Heidmann and M.J. Klein (Springer-Verlag), pp. 71-79.

1991 Kawaguchi, K., N. Kaifu, M. Ohishi, Y. Hirahara, S. Ishikawa, S. Yamamoto, S. Saito, S. Takano, A. Murakami, J.M. Vrtilik, P. Thaddeus, and W.M. Irvine, "The Cumulene Carbenes H<sub>2</sub>C<sub>4</sub> and H<sub>2</sub>C<sub>3</sub> in TMC-1", *Publ. Ast. Soc. Japan*, **43**, 607.

1991 Madden, S.C., "Results of a Galactic Survey for the Ring Molecule Cyclopropenylidene (C<sub>3</sub>H<sub>2</sub>)", in *Chemistry in Space*, ed. J.M. Greenberg and V. Pirronello (Kluwer Acad. Publ.), pp. 437-438.

1991 Minh, Y. and W.M. Irvine, "Interstellar H<sub>2</sub>S: Probe of Grain Surface Chemistry", in *Chemistry in Space*, ed. J.M. Greenberg and V. Pirronello (Kluwer Acad. Publ.), pp. 435-436.

1991 Minh, Y.C., W.M. Irvine, and M.K. Brewer, "H<sub>2</sub>CS Abundances and Ortho-to-Para Ratios in Interstellar Clouds", *Astron. Astrophys.*, **244**, 181.

1991 Minh, Y.C., L.M. Ziurys, W.M. Irvine, and D. McGonagle, "Abundances of Hydrogen Sulfide in Star Forming Regions", *Astrophys. J.*, **336**, 192.

1991 Minh, Y.C. and W.M. Irvine, "Upper Limits for the Ethyl Cyanide Abundances in TMC-1 and L134N: Chemical Implications", *Space Sci.*, **175**, 165.

1991 Minh, Y.C., M.K. Brewer, W.M. Irvine, P. Friberg, and L.E.B. Johansson, "Abundance and Chemistry of Interstellar HOCO<sup>+</sup>", *Astron. Astrophys.*, **244**, 470.

1991 Ohishi, M., K. Kawaguchi, N. Kaifu, W.M. Irvine, Y.C. Minh, S. Yamamoto, and S. Saito, "The Ortho-to-Para Ratio for Ketene in TMC-1", in *Skylines: New Results in Spectral Line Astrophysics*, ed. A. Haschick and P.T.P. Ho, Astron. Soc. Pacific Conf. Ser., **16**, 387.

1991 Ohishi, M., H. Suzuki, S-I. Ishikawa, C. Yamada, H. Kanamori, W.M. Irvine, R.D. Brown, P.D. Godfrey, and N. Kaifu, "Detection of a New Carbon-Chain Molecule, CCO", *Astrophys. J. (Lett.)*, **380**, L39.

1991 Ziurys, L.M., D. McGonagle, and Y.C. Minh, "Nitric Oxide in Star-forming Regions: Further Evidence for Interstellar N-O Bonds", *Astrophys. J.*, **373**, 535.

1992 Bergman, P., Å. Hjalmarsen, P. Friberg, W.M. Irvine, T.J. Millar, M. Ohishi, and S. Saito, "Results from a Three Position Spectral Scan in the Sgr B2 Molecular Cloud Core", in *Astrochemistry of Cosmic Phenomena (IAU Symposium 150)*, ed. P.D. Singh, Kluwer, pp. 179-180.

1992 Brown, R.D., D. Cragg, P.D. Godfrey, W.M. Irvine, and M. Ohishi, "Recent Detections of New Interstellar Molecules: a New Oxide of Carbon, C<sub>2</sub>O", *Origin Life Evol. Biosphere*, **21**, 399.

1992 Irvine, W.M., "Cold, Dark Interstellar Clouds: Can Gas Phase Reactions Explain the Observations?", in *Chemistry and Spectroscopy of Interstellar Molecules*, ed. N. Kaifu (Univ. Tokyo Press), p. 47-55.

1992 Irvine, W.M., "Chemistry of the Cosmos", in *Frontiers of Life*, ed. J. Tran Thanh Van et al., Editions Frontieres, France, pp. 263-290. (Invited Review)

1992 McGonagle, D., W. Irvine, and Y. Minh, "Nitrogen Sulfide (NS) in Star Forming Regions", in *Astrochemistry of Cosmic Phenomena (IAU Symposium 150)*, ed. P.D. Singh, Kluwer, pp. 227-230.

1992 Minh, Y.C., W.M. Irvine, and P. Friberg, "Molecular Abundances in the Sgr A Molecular Cloud", *Astron. Astrophys.*, **258**, 489.

1992 Minh, Y.C., W.M. Irvine, and P. Friberg, "Molecular Abundances in the Sgr A Molecular Cloud", in *Astrochemistry of Cosmic Phenomena (IAU Symposium 150)*, ed. P.D. Singh, Kluwer, pp. 223-224.

1992 Ohishi, M., W.M. Irvine, and N. Kaifu, "Molecular Abundance Variations among and within Cold, Dark Molecular Clouds", in *Astrochemistry of Cosmic Phenomena (IAU Symposium 150)*, ed. P.D. Singh, Kluwer, pp. 171-177.

1992 Swade, D.A. and F.P. Schloerb, "A Source Model for the L134N Molecular Cloud", *Astrophys. J.*, **392**, 543.

1992 Ungerechts, H., E.A. Bergin, J. Carpenter, P.F. Goldsmith, W.M. Irvine, A. Lovell, D. McGonagle, F.P. Schloerb, and R.L. Snell, "Chemical Gradients in the Orion Molecular Cloud, in *Astrochemistry of Cosmic Phenomena (IAU Symposium 150)*, ed. P.D. Singh, Kluwer, pp. 271-274.

1993 Lee, C.W., Y.C. Minh, and W.M. Irvine, "Observations of  $C_3H_2$  ( $2_{12}-1_{01}$ ) toward the Sagittarius A Molecular Cloud", *J. Korean Ast. Soc.*, **26**, 73.

1993 McGonagle, D., and W.M. Irvine, "Recent Developments in Interstellar Chemistry", in *Recent Developments in Millimeter-wave and Infrared Astronomy*, ed. S.H. Cho and H.S. Chung, Korea Astronomy Observatory, Daejeon, pp. 65-76.

1993 McGonagle, D., W.M. Irvine, and M. Ohishi, "Nitrogen Sulfide in Quiescent, Dark Clouds", *Astrophys. J.*, **422**, 621.

1993 Minh, Y.C., W.M. Irvine, and M. Ohishi, "The Relative Abundances of the A and E Symmetry Species of  $CH_3CN$  in the Cold Cloud TMC-1", *Astron. Astrophys.*, **267**, 229.

1993 Minh, Y.C., M. Ohishi, D.G. Roh, M. Ishiguro, and W.M. Irvine, "Interferometric Observations for Oxygen-Containing Organic Molecules toward Ori KL", *Astrophys. J.*, **411**, 773.

1993 Minh, Y.C., Irvine, W.M., and McGonagle, D., "A Search for  $\text{H}_2\text{COH}^+$  and  $\text{H}_2^{13}\text{CO}$  in Dense Interstellar Molecular Clouds", *J. Korean Ast. Soc.*, **26**, 99.

1993 Ziurys, L.M. and D. McGonagle, "The Spectrum of Orion KL at 2mm (150-160 GHz)", *Astrophys. J. Suppl.*, **89**, 155.

1994 Bergin, E.A., Goldsmith, P.F., Snell, R.L., and Ungerechts, H., " $\text{CH}_3\text{C}_2\text{H}$  as a Temperature Probe in GMC Cores", *Astrophys. J.*, **431**, 674.

1994 Fukusaku, S., Hirahara, Y., Masuda, A., Kawaguchi, K., Ishikawa, S., Kaifu, N., and Irvine, W.M., "Observations of Molecular Envelopes of Late-type Stars: CRL618, CRL2688, CRL3068 and CIT6", *Astrophys. J.*, **437**, 410.

1995 Irvine, W.M., "Organic Molecules in the Gas Phase of Dense Interstellar Clouds", *Adv. Space Res.*, **15**, (3)35. Invited Review.

1994 Ohishi, M., S. Yamamoto, S. Saito, D. McGonagle, and W.M. Irvine, "Detection of a New Interstellar Molecule,  $\text{CH}_2\text{N}$ ", *Astrophys. J. (Lett.)*, **427**, L51.

1994 Pratap, P., Menten, K.M., Snyder, L.E. "Detection of Formaldehyde Maser Emission near the Ultracompact HII Region G29.96-02", *Astrophys. J.*, **430**, L129.

1994 McGonagle, D., Irvine, W.M., and Ohishi, M., "Nitrogen Sulfide in Quiescent Dark Clouds", *Astrophys. J.*, **422**, 621.

1994 Pratap, P., Irvine, W.M., Schloerb, F.P., Snell, R.L., Bergin, E.A., Miralles, M.P., Dickens, J., and McGonagle, D., "Millimeter Observations of TMC-1 and L134N", in *Clouds, Cores and Low Mass Stars*, ed. D.P. Clemens and R. Barvainis, ASP Conf. Ser. **65**, pp. 25-29.

1995 Ungerechts, H., Bergin, E.A., Goldsmith, P.F., Irvine, W.M., Schloerb, F.P., and Snell, R.L., "Chemical and Physical Gradients along the OMC-1 Ridge", in *The Physics and Chemistry of Interstellar molecular Clouds*, ed. G. Winnewisser and G. Pelz, Springer, pp. 258-264.

1995 Minh, Y.C., Dickens, J.E., Irvine, W.M., and McGonagle, D., "Measurements of the H<sub>2</sub><sup>13</sup>CO Ortho/Para Ratio in Cold, Dark Molecular Clouds", *Ast. Astrophys.*, **298**, 213.

1996 Dickens, J.E., Irvine, W.M., Ohishi, M., Arrhenius, G., Pitsch, S., Bauder, A., Müller, F., and Eschenmoser, A., "A Search for Interstellar Oxiranecarbonitrile (C<sub>3</sub>H<sub>3</sub>NO)", *Origins Life Evol. Biosphere*, **26**, 97.

1996 McGonagle, D., and Irvine, W.M., "A Search for HCCN in Molecular Clouds", *Ast. Astrophys.*, **310**, 970.

1996 Minh, Y.C., Park, Y.S., Kim, K.T., Irvine, W.M., Brewer, M.K. and Turner, B.E., "The High Latitude Cloud MBM7. I. HI and CO Observations", *Astrophys.J.*, **467**, 717.

1996 Ohishi, M., Ishikawa, S.-I., Amano, T., Oka, H., Irvine, W.M., Dickens, J.E., Ziurys, L.M. and Apponi, A.J., "Detection of a New Interstellar Molecular Ion, H<sub>2</sub>COH<sup>+</sup> (Protonated Formaldehyde)", *Astrophys.J.*, **471**, L61.

1996 Irvine, W.M., Bockelee-Morvan, D., Lis, D., Matthews, H.E., Biver, N., Crovisier, J., Davies, J.K., Dent, W.R.F., Gautier, D., Godfrey, P.D., Keene, J., Lovell, A.J., Owen, T.C., Phillips, T.G., Rauer, H., Schloerb, F.P., Senay, M., and Young, K., "Spectroscopic Evidence for Interstellar Ices in Comet Hyakutake", *Nature*, **383**, 418.

1997 Dickens, J.E., Irvine, W.M., DeVries, C. and Ohishi, M., "Hydrogenation of Interstellar Molecules: A Survey for Methylenimine (CH<sub>2</sub>NH)", *Astrophys.J.*, **479**, 307.

1997 McGonagle, D., and Irvine, W.M., "Nitrogen Sulfide in Giant Molecular Clouds", *Astrophys.J.*, **477**, 711.



1997 Irvine, W.M., "Extraterrestrial Organic Matter: A Review", *Origins Life Evol. Biosphere*, in press. Invited review.

1997 Bergin, E.A., Ungerechts, H., Goldsmith, P.F., Snell, R.L., Irvine, W.M., and Schloerb, F.P., "A Survey of the Physical and Chemical Properties of the M17 and Cepheus A Cloud Cores", *Astrophys.J.*, **482**, 267.

1997 Ungerechts, H., Bergin, E.A., Goldsmith, P.F., Irvine, W.M., Schloerb, F.P., and Snell, R.L., "Chemical and Physical Gradients along the OMC-1 Ridge", *Astrophys.J.*, **482**, 245.

1997 Pratap, P., Dickens, J.E., Snell, R.L., Miralles, M.P., Bergin, E.A., Irvine, W.M., and Schloerb, F.P., "A Study of the Physics and Chemistry of TMC-1", *Astrophys. J.*, in press.

1997 Dickens, J.E., Irvine, W.M., Ohishi, M., Ikeda, M., Ishikawa, S., Nummelin, A. and Hjalmarsen, Å., "Detection of Interstellar Ethylene Oxide ( $c\text{-C}_2\text{H}_4\text{O}$ )", *Astrophys. J.*, in press.

1997 Irvine, W.M., DeVries, C.H., Dickens, J.E., Lovell, A.J., Schloerb, F.P., Senay, M., Jewitt, D., and Matthews, H.E, "Interstellar and Cometary Ices: Molecular Emission from Comet Hale-Bopp", in *The Far Infrared and Submillimetre Universe*, ESA SP-401, in press.

#### B. Ph.D. Dissertations:

1990 Madden, S.C., "A Multi-transition Study of the Cyclic Molecule Cyclopropenylidene ( $\text{C}_3\text{H}_2$ ) in the Galaxy," Ph.D. Thesis, University of Massachusetts.

1990 Minh, S.C., "Radio Observations of Several Interstellar Molecules", Ph.D. Thesis, University of Massachusetts.

1995 McGonagle, D. "Nitrogen Chemistry in the Interstellar Medium", Ph.D. Thesis, University of Massachusetts.

C. Recent Abstracts, Reports, and Popular Articles:

1990 Ziurys, L.M., D.M. McGonagle, and Y. Minh, "Nitric Oxide in Star-forming Regions", *Bull. Amer. Astron. Soc.*, **22**, 1798.

1991 Bergin, E.A., P.F. Goldsmith, R.L. Snell, and H. Ungerechts, "Physical Conditions along the Orion Molecular Cloud Ridge", *Bull. Amer. Astron. Soc.*, **23**, 1372.

1991 Kress, M.E., C.M. Leung, and W.M. Irvine, "Probing the Carbon-to-Oxygen Ratio in Dense Interstellar Clouds", *Bull. Amer. Astron. Soc.*, **23**, 1370.

1991 Ungerechts, H., E.A. Bergin, J. Carpenter, P.F. Goldsmith, W.M. Irvine, A.Lovell, D. McGonagle, F.P. Schloerb, and R.L. Snell, "Chemical Gradients in the Orion Molecular Cloud", *Bull. Amer. Astron. Soc.*, **23**, 1372.

1992 Irvine, W.M., "Interstellar Chemistry and the Origin of Life", *ACCUMU* (Japan), **4**, 72.

1993 McGonagle, D., and Irvine, W.M., "The Large Millimeter-wave Telescope", in *Recent Developments in Millimeter-wave and Infrared Astronomy*, ed. S.H. Cho and H.S. Chung, Korea Astronomy Observatory (Daejeon, Korea), pp. 65-76.

1993 Ziurys, L.M., and D. McGonagle, "The Spectrum of Orion KL at 2mm (150-160 GHz)", *Bull. Amer. Ast. Soc.*, **24**, 1146.

1996 Lovell, A.J., Schloerb, F.P., Dickens, J.E., DeVries, C.H., and Irvine, W.M., "Molecular Observations of Comet C/1996 B2 Hyakutake", *Bull. Amer. Ast. Soc.*, **28**, 1091.

1996 Schloerb, F.P., Lovell, A.J., Dickens, J.E., DeVries, C.H., and Irvine, W.M., "Mapping of HCN in the Coma of Comet C/1996 B2 Hyakutake", *Bull. Amer. Ast. Soc.*, **28**, 1091.

1996 Irvine, W.M., "Extraterrestrial Organic Chemistry: A Source of Prebiotic Molecules?", *Origins Life Evol. Biosphere*, **26**, 203.

1996 Irvine, W.M. and Dickens, J.E., "Hydrogenation of Interstellar Molecules: A Survey for Methylenimine", *Origins Life Evol. Biosphere* **26**, 323.

1996 Irvine, W.M., Lovell, A.J., Schloerb, F.P., Senay, M., Jewitt, D., Owen, T., Matthews, H.E., Biver, N., Bockelee-Morvan, D., Crovisier, J., Gautier, D., and Rauer, H., "Interstellar and Cometary Ices: Molecular Emission from Comet 1996 B2", *Origins Life Evol. Biosphere*, **26**, 325.

1997 Nummelin, A., Hjalmarson, Å., Bergman, P., Friberg, P., Millar, T.J., Irvine, W.M., Ohishi, M., and Saito, S., "A 3-position Spectral Line Survey of the Sgr B2 Molecular Cloud", in *CO- 25 Years of Millimeter-Wave Spectroscopy*, ed. W.B.Latter *et al.*, Kluwer, p.444.

1996 Matthews, H.E., Jewitt, D. and Irvine, W.M., "Comet C/1996 O1 (Hale-Bopp)", *Intl. Astron. Union Circ.* 6515.

1997 Lovell, A.J., Schloerb, F.P., Dickens, J.E., DeVries, C.H., Irvine, W.M., and Senay, M., "Comet C/1996 O1 (Hale-Bopp)", *Intl. Astron. Union Circ.* 6590.

1997 Pratap, P., Bergin, E.A., Dickens, J., Irvine, W.M., Miralles, M., Schloerb, F.P., and Snell, R.L., "A Chemical Survey of the Dark Clouds TMC-1 and L134N", in *CO- 25 Years of Millimeter-Wave Spectroscopy*, ed. W.B.Latter *et al.*, Kluwer, p.447.

