NATIONAL RADIO ASTRONOMY OBSERVATORY

THE 25-m MILLIMETER WAVELENGTH TELESCOPE

April 4, 1979

1. INTRODUCTION

The National Radio Astronomy Observatory proposes to build a radio telescope of diameter 25 meters, having a surface accuracy of 75 μm, to permit operation to wavelengths of 1.2 mm and shorter. The chosen site is the low-latitude, high-altitude Science Reserve on the summit of Mauna Kea, Hawaii.

This state-of-the-art instrument will allow astronomers to take full advantage of the millimeter-wavelength region of the electromagnetic spectrum. Specifically, it will help develop the new subject of astrochemistry, investigate star formation on galactic and extragalactic scales in regions otherwise inaccessible because of optical extinction, and attack the fundamental problem of the structure and evolution of galaxies by measuring the amount and composition of their gas content. It will be a powerful instrument for investigating activity in the nuclei of galaxies and quasars by permitting continuum observations in the wavelength region between the traditional optical and radio domains. It can also explore the atmospheres and surfaces of planets, satellites, and asteroids within our own solar system.

2. SCIENTIFIC NEED

Millimeter-wave astronomy, now approximately ten years old, includes the spectral region from roughly 1 mm to 1 cm, or 300 to 30 GHz. The peculiar advantage derived from the millimeter region of the spectrum is two-fold. First, it permits the astronomer to examine the dark, cold regions of the interstellar gas by means of the radiation from molecules which form there. Second, it permits astronomers to examine sources of continuum radiation at wavelengths midway between the traditional optical and radio spectral regions.

Observations in this spectral region have given new insight into the nature of the interstellar gases, the formation of stars, the evolution of galaxies, and the nature of explosive events in quasars and the nuclei of radio galaxies. They have also stimulated a new field of astronomical research now known as astrochemistry. These areas will be discussed in more detail below. Other research areas have also received large impetus with the advent of millimeter-wave observations. Among these are the study of planets and their atmospheres, comets, evolved stars and their interaction through mass loss with the interstellar gases, the evolution of planetary nebulae, the distribution of isotopes in the galaxy, and the distribution of molecules in external galaxies.

A. Molecular Clouds and Star Formation

Stars form from and disintegrate into the gas and dust known as the interstellar medium. The extinction of light by this medium allows only a limited study by optical techniques. The fundamental wavelengths emitted by the embedded molecules lie in the millimeter range. Through millimeter-wave astronomy, it is now known that approximately half of the mass of the interstellar medium is in the form of molecules, in clouds or cloud complexes which vary from about 3 to 300 light years in size and from 1 to $10^6\ M_{\odot}$ in mass. Stars form from these clouds. Except for hydrogen and some fraction of helium, the atoms in these clouds were formed in nucleosynthesis from stars long gone.

The distribution of the molecular clouds has been measured on an overall galactic scale. Several hundred thousand clouds are concentrated in the galactic nucleus and within an annulus between 12,000 and 25,000 light years from the galactic center. Within these regions the space-averaged abundance of the molecules exceed that of atoms by a factor of at least 5. This unexpected abundance of molecules has sharply changed our understanding of large-scale star formation within our galaxy. For a number of years it has been known that the space-averaged abundance of atoms decreases in the inner part of the galaxy. This decrease was presumed to be due to vigorous star formation in the galactic interior, such that the process of star formation depleted the interstellar gas. It is now clear that large amounts of gas do exist in the galactic interior, but in the form of molecules, thus providing the material from which a new generation of stars can form.

Many sites of star formation have been found by observations of molecular lines at millimeter wavelengths. In some cases these observations have been supplemented with observations of continuum emission in the millimeter and infrared regions. Typically, when densities within a cloud exceed 10^6 cm-3, intense maser emission occurs from several molecules. The most common molecular masers are OH and H_2O. In the same locale are usually found molecular lines having very broad wings. These broad wings indicate a rapid flow of mass as would be expected in the earliest stages of star formation. Often observations of millimeter continuum emission from the same regions show the presence of heated dust and compact sources of ionized gas characteristic of newly formed stars. In objects close to the sun, these ionized regions appear as parts of large molecular clouds. In the Northern Hemisphere the most spectacular example is the Orion Nebula, an example of a large cloud which is undergoing successive bursts of star formation.

All stages of this star formation process have been found by millimeter-wave astronomy. For the first time it is possible to investigate star formation on a quantitative basis. These data permit tests of, and refinement to, star formation theories developed over the last four decades.

The physical conditions within the clouds are also an important area of study. Observations of molecular emission lines show that cloud temperatures range from 6 K when there are no internal energy sources to 90 K when protostellar or stellar objects are embedded. Within the clouds, densities range from 10^3 atoms per cm^{-3} in diffuse clouds to as large as 10^8 cm^{-3} in highly compact regions within some giant complexes. Sometimes the distribution of velocities within the clouds suggest the clouds to be rotating. A few clouds appear to be collapsing, showing that their internal gravitational forces dominate over internal turbulence, centripetal forces, and magnetic and radiation pressure. The balance of these forces are fundamental to our understanding of how stars form, and to the energy balance and flow within the interstellar medium.

B. Interstellar Chemistry

The new subject of astrochemistry derives from the types and abundances of molecules within the clouds. It deals with the theories of molecular formation and destruction in the interstellar medium. At this time, more than 50 molecules have been observed. Adding the isotopically substituted species which have been seen, including ^{2}H, ^{13}C, ^{17}O, ^{18}O, ^{15}N, ^{33}S, ^{34}S, ^{29}Si, and ^{30}Si, increases this number to more than 100. Several molecular species were detected and identified by radio astronomers before they were even synthesized in terrestrial laboratories. The low temperatures of the molecular clouds have permitted the direct observation of hyperfine splitting in HNC and N_2H^+, which cannot be resolved in the laboratory. Furthermore, accurate microwave frequencies have been determined astronomically for several species inaccessible in the laboratory. These species include HCO^+, N_2H^+, HNC, CH, C_2H, and C_3N. These observations provide basic spectroscopic data required to understand the structure of these molecules and radicals.

The formation of astronomical molecules occurs generally under conditions quite unlike those on earth. The study of interstellar chemistry permits an investigation of chemical reactions not easily duplicated in the laboratory. Primarily because of millimeter-wave astronomy, the chemistry of ion-molecule gas reactions has experienced a major impetus in the last four years. Catalytic reactions on dust grains may also be important in the interstellar medium, and recent laboratory work has been devoted to this area.

C. Extragalactic and Cosmological Objects

Although to date millimeter-wave astronomy has had its greatest impact on galactic problems through observations of molecular clouds, millimeterwave observations of continuum emissions have grown in importance. Cold regions have recently been detected in the isotropic cosmic radiation in the directions of several rich clusters of galaxies. One explanation is that the background radiation in these directions has been scattered

by a tenuous hot gas comprising an intergalactic medium. For some years the existence of this gas has been predicted by astronomers on the basis of satellite observations of X-rays. The mm-wave observations tend to confirm the presence of the long-conjectured intergalactic gas.

The radiation from a number of extragalactic objects varies with wavelength in diverse ways which are poorly understood. Objects which are optically bright and variable usually exhibit a constant or increasing radiation intensity from centimeter to millimeter wavelengths. In at least one object, A0235+164, an intense outburst occurred simultaneously at optical and millimeter wavelengths, indicating a close relationship between the optical and radio variability. The polarization of another object, 0J287, has the same position angle observed at millimeter and near-IR wavelengths. Observations such as these may direct our analysis of the energetics and emission mechanisms of these cosmological objects.

Other important observations have been made of galaxies at millimeter wavelengths. The nuclei of the cores of several double radio galaxies have been observed to be strong emitters at millimeter wavelengths. The fact that several of these objects have also been detected as X-ray sources suggests that these objects may be cooling by means of the Compton effect.

3. IMPACT ON THE FIELD OF ASTRONOMY

Although the 36-ft telescope continues to be in heavy demand, an increasing fraction of the important research proposals are being limited by the restrictions of angular resolution, sensitivity, and wavelength range which are intrinsic to this telescope. It has a smaller collecting area than is needed and cannot operate well at wavelengths shorter than 2.4 mm. While recent advances in radiometer technology offer an improvement in sensitivity, the limitations on resolution and wavelength range can only be removed by the construction of a larger telescope with a more precise surface. Certain research areas, involving sources with high surface brightness and small-scale angular structure, will require a millimeter-wave interferometer. However, the wide range of astronomical problems which can be addressed by millimeter-wave observations needs not only the higher angular resolution but also the sensitivity and frequency flexibility provided by a large, filled aperture.

The proposed 25-m telescope offers a 5-fold increase in collecting area at wavelengths now covered by the 36-ft telescope. It extends the frequency range of the 36-ft by more than 1 octave. And, the high altitude and low latitude of the Mauna Kea site minimizes the fundamental limitation of atmospheric absorption.

4. STATUS OF THE TELESCOPE DESIGN

The 25-m telescope is based upon a homologous design, a principle developed at the NRAO over the past ten years by S. von Hoerner. A millimeter-wave telescope requires an extremely precise surface. In this case the design calls for a paraboloid surface with rms deviations less than 75 μm. Conventionally designed telescopes usually involve a truss structure supporting surface panels and feed, movable in both elevation and azimuth. Gravitational deformation of these structures occurs by a sagging of the surface panels between the hard support points, and by an overall deterioration of the entire surface from a paraboloid. While this deformation can never be avoided, careful design renders it harmless in terms of radiometric performance. First, the surface is supported by many points close together, resulting in equal softness of the truss structure. Second, the truss structure is designed so that it always deforms into a parabolic surface, albeit of differing focal length. The use of a truss structure which is insensitive to gravitational deformation by means of controlled flexure, is called a homolgous design.

It is important to emphasize that, while the design of the telescope utilizes advanced concepts, the analysis of the design is performed by standardized structural programs such as NASTRAN or STRUDL. The NRAO design program has been developed and used for many years to produce designs for 100-m, 65-m and 25-m telescopes. Analysis of the 25-m telescope design by conventional structural programs predicts excellent performance. To investigate further the effects of manufacturing irregularities in the steel tubing, a variational analysis has been developed. The performance figures given in the NRAO proposal use this "worst case" estimate.

One homologous telescope, the 100-m radio telescope of the Max-Planck-Institut at Effelsburg, West Germany is in operation. Its performance is as predicted by the designers, thereby proving the effectiveness of a homology design. The United Kingdom is also using a homology design for its proposed millimeter-wave telescope.

Volumes I and II of the proposal outlining the requirements for, performance of and estimated cost of this radio telescope have been submitted. Every design goal of the 25-m telescope has now been met by a specific concept, proven either by actual experiment or by computer analysis. Considerable research and development has been done to accomplish this. Prototype surface plates have been manufactured, a prototype of the surface adjustment device has been made, and surface measurement equipment has been developed which can meet the specifications. A computer analysis has been made of the conceptual design. A computer analysis has been made of the conceptual astrodome design. An exact location for the telescope on Mauna Kea, Hawaii has been chosen. A conceptual site plan at this location has been made. A conceptual plan for a building at the telescope has been made. Contacts, or informal agreements, have been established with other research groups and the University of Hawaii, operating on Mauna Kea, to keep abreast of problems

and special requirements in operating research equipment at this site. This experience is incorporated into our final design and construction plans, where applicable.

The major steps in this project, from the site choice to the telescope design, have been taken. The procurement and construction sequence have been identified and ordered by the management program PERT (project evaluation and review technique). The NRAO is now ready to proceed with the detailed design and construction of this telescope.

5. SIZE OF SCIENTIFIC COMMUNITY INVOLVED: MILLIMETER-WAVELENGTH

The 36-ft telescope has been attracting both radio astronomers and chemists. Last year 48 institutions used the telescope, including 104 visitors, 14 graduate students, 2 postdoctoral students, and 12 members of the NRAO permanent staff. The NRAO list of staff and visitor publications for 1978 include theoretical, observational, and engineering articles. Fifty-three publications, approximately 25 percent of the total number, involved observations made with the 36-ft telescope. An example of the interdisciplinary nature of the astrochemistry is the cover story, a 13-page special report, featured in the October 2, 1978 issue of Chemical and Engineering News, a widely read journal of the American Chemical Society. This article "Chemistry of Interstellar Space" presents an excellent and up-to-date summary of this subject.

6. DETAILED DESCRIPTION OF THE PROJECT

A. Cost Estimate

For the purposes of planning costs, the NRAO has divided the project into non-recurring and recurring costs. The non-recurring costs include detailed design, construction of astrodome and telescope, construction of the buildings on the summit and the base support building in Kamuela. The recurring costs begin when the telescope goes into operation. They do not include the cost of radio receivers, which are included in the overall operations budget of the NRAO.

To obtain the current estimate of cost, we have started from the estimates listed in Volume II of the Proposal, which were based on actual bidding experience. To adjust these costs from the 1976 base of the proposal to an effective date of December 31, 1978, we have used the construction index for high-rise buildings in Honolulu, which we believe is the index most appropriate for our project. This index has experienced an annual increase of 10 percent. The forward projections assume a continued inflation rate of 10 percent per year.

For non-recurring costs, the NRAO has prepared three funding plans, given in Appendix 1. Plan A, The Optimum Plan, assumes $4.4M in 1981 and the balance in 1982. Even though the project will not be completed until March 30, 1982, Plan A gives the most favorable price, $22,850k. Plan B assumes $4.4M in 1981 and two subsequent years of funding. Construction will be complete on May 22, 1984. The cost is $25,390k. Finally, Plan C assumes $4.4M in 1981, followed by three years of funding. Here construction will not be complete until May 24, 1985. The cost is $27,080.

B. Project Management

The NRAO plans to act as prime contractor for this project. Through our project office the detailed design of telescope, astrodome, and buildings will be prepared. When the detailed design is completed, contracts will be sought for the construction of the telescope, the astrodome, the summit buildings, and the buildings in Kamuela. The latter are called the base support facility. Appendix 2 describes the project management in more detail.

C. Annual Operating Costs

Recurring costs have been calculated on the basis of our operating experience in Tucson and on Kitt Peak, and on the actual 1979 operating budget of the Canada-France-Hawaii telescope corporation now operating in Hawaii. Because of our planned close working relationship with CFH and with the United Kingdom infrared telescope, we plan a salary schedule and personnel benefits parallel to what they are now using. The anticipated costs have been estimated in current dollars, as shown in Appendix 3; the costs projected to 1985 assume an inflation rate of 7 percent.

D. Associated Equipment

Based on our experiences in Green Bank and on Kitt Peak, we plan to install a computer system at the summit which is adequate for astronomers to take and reduce data. In principle an astronomer will leave the mountain after his telescope run with his data in a reduced form. No extensive computer facilities are planned for the base support facility except those required for engineering and business use.

The method of preparing receivers will also parallel that now in use at Kitt Peak. At NRAO headquarters, a high-level engineering group will develop and refine critical elements of a receiver system. When completed, these elements will be shipped to Hawaii where the on-site engineering staff will incorporate them into receivers for use on the mountain. Because of its distance from the mainland, the technical group of the base support facility will require a number of senior engineers.

NRAO is currently engaged in the development of receivers for frequencies to 300 GHz. Of particular interest for the 25-m telescope are mixers, Josephson effect devices and bolometers. For example, NRAO is presently constructing a bolometer system which will work at 3 mm, 2 mm, and 1 mm wavelength. Further development is, of course, planned as technology permits.

E. Implied Grant Support

So far as we are able, the NRAO plans to continue its program of travel support for astronomers using the Mauna Kea telescope. In this way any geographic penalty due to travel may be minimized.

F. Lifetime of the Facility

The useful lifetime of the telescope will be at least 20 years. It is, of course, impossible to estimate the life expectancy as a forefront instrument, but this expectation seems reasonable, on the basis of our experience with the NRAO 140-ft and 300-ft telescopes.

7. PROJECT MILESTONES

Three different construction schedules have been developed, corresponding to the three funding schedules described in Appendix 1. The construction schedules have been planned using PERT, and are summarized in Appendix 4.

A. Two-Year Funding

1981 - Design telescope, astrodome, buildings and site development.
- Begin procurement of surface plates.

1982 - Begin procurement of telescope, astrodome, and buildings.
- Complete foundations of telescope and astrodome.
- Install telescope tower.
- Complete site utilities.

1983 - Complete telescope, astrodome and buildings.

1984 - Complete test of telescope.

B. Three-Year Funding

1981 - Design telescope, astrodome, buildings and site development.
- Begin procurement of surface plates.

1982 - Begin procurement of telescope and astrodome.
- Complete foundations of telescope and astrodome.
- Install telescope tower.
- Complete site utilities.

1983 - Complete the astrodome.
- Complete the telescope, except for the installation and setting of the plates.
- Complete the site buildings.

1984 - Complete the telescope, and the tests of the telescope.

C. Four-Year Funding

1981 - Design telescope, astrodome, buildings, and site development.
- Begin procurement of surface plates.

1982 - Complete the foundations for the telescope and astrodome.
- Begin construction of the astrodome.
- Complete the site utilities.

1983 - Begin construction of the telescope, completing the installation of the tower.
- Complete the main construction phase of the astrodome.

1984 - Complete the astrodome and telescope
- Start and complete the site buildings.

1985 - Complete the site development and test the telescope.

APPENDIX 1. COST AND FUNDING SCHEDULES

This appendix presents the detailed cost estimates for three funding schedules. The costs are based on the estimates presented in Volume II of the proposal, except that they have been updated to December, 1978 using the construction index for high-rise buildings in Honolulu. This index has increased at a rate of 10 percent per year. The same rate has been used to project the costs forward from the base of December, 1978 to the construction years 1981-84.

In the following tables, each of the main contracts has been subdivided into major activities. These subdivisions are as follows:

Telescope -	Part 1	Surface Plates
	Part 2	Intermediate Panels, Backup Structure, Counterweights, Bearings and Drives, Tower Structure, Freight, High Altitude Construction Premiums
	Part 3	Computer
	Part 4	Feed Support, Subreflector, Servo, Ladders, Cabling, Painting, Final Setting, Electronic Interface, Intercom, Boresight Telescope, Visitor Area
	Part 5	Telescope Foundations
Astrodome -	Part 1	Astrodome
	Part 2	Air Handling and Crane
Site Development -	Part 1	Water, Electricity, Grading, Access Roads
	Part 2	Buildings at the Telescope Site
	Part 3	Base Level Facility

The funding schedules A, B, and C, representing two-year, three-year, and four-year funding are given in Tables 1-1, 1-2, and 1-3.

TABLE 1-1

25-m Telescope Construction Funding Plans
(in thousands of dollars)

		1976$ (proposal)	1978$	Construction Plan A 1981	1982	Sum
			(2)	(2)	(2)	(2)
Telescope	Design	477	580	770		770
	Const. Part 1	1234	1510	2000		2000
	Const. Part 2	1905	2330		3410	3410
	Const. Part 3	331	400		590	590
	Const. Part 4	731	890		1310	1310
	Const. Part 5	260	320		470	470
Astrodome	Design	467	570	760		760
	Const. Part 1	3709	4530		6640	6640
	Const. Part 2	342	420		610	610
Site	Design	194	240	310		310
	Const. Part 1	300	370		540	540
	Const. Part 2	875	1070		1570	1570
	Const. Part 3	577	700		1030	1030
Burden (7% of construction)[3]		-	-	-	-	-
Project Management1)		-	-	160	600	760
Subtotal		11402	13930	4000	16770	20770
Contingency (10%)		1140	1390	400	1680	2080
TOTAL		12542	15320	4400	18450	22850

1) Assumes an average of 12 people during life of construction project. (Not included in original estimate.)

2) Actual escalation to 1978, assumed 10% per year 1978 →

3) Burden is the estimated extra cost because of stretched out funding (smaller contracts, in and out costs, etc.).

TABLE 1-2

25-m Telescope Construction Funding Plans
(in thousands of dollars)

		1976 (proposal)	1978$	Construction Plan B			
				1981	1982	1983	Sum
			(2)	(2)	(2)	(2)	
Telescope	Design	477	580	770			770
	Const. Part 1	1234	1510	2000			2000
	Const. Part 2	1905	2330		3410		3410
	Const. Part 3	331	400			650	650
	Const. Part 4	731	890			1430	1430
	Const. Part 5	260	320		470		470
Astrodome	Design	467	570	760			760
	Const. Part 1	3709	4530		6640		6640
	Const. Part 2	342	420			670	670
Site	Design	194	240	310			310
	Const. Part 1	300	370		540		540
	Const. Part 2	875	1070			1710	1710
	Const. Part 3	577	700			1130	1130
Burden (7% of construction)[3]		-	-	-	770	390	1160
Project Management[1]		-	-	160	600	670	1430
Subtotal		11402	13930	4000	12430	6650	23080
Contingency (10%)		1140	1390	400	1240	670	2310
TOTAL		12542	15320	4400	13670	7320	25390

[1] Assumes an average of 12 people during life of construction project. (Not included in original estimate.)

[2] Actual escalation to 1978, assumed 10% per year 1978 →

[3] Burden is the estimated extra cost because of stretched out funding. (Smaller contracts, in and out costs, etc.)

TABLE 1-3

25-m Telescope Construction Funding Plans (in thousands of dollars)

		1976$ (proposal)	1978$	Construction Plan C				
				1981	1982	1983	1984	Sum
			(2)	(2)	(2)	(2)	(2)	
Telescope	Design	477	580	770				770
	Const. Part 1	1234	1510	2000				2000
	Const. Part 2	1905	2330			3740		3740
	Const. Part 3	331	400				710	710
	Const. Part 4	731	890			1430		1430
	Const. Part 5	260	320		470			470
Astrodome	Design	467	570	760				760
	Const. Part 1	3709	4530		6640			6640
	Const. Part 2	342	420				740	740
Site	Design	194	240	310				310
	Const. Part 1	300	370		540			540
	Const. Part 2	875	1070				1890	1890
	Const. Part 3	577	700				1250	1250
Burden (7% of construction)[3]		-	-	-	540	360	320	1220
Project Management 1)		-	-	160	600	670	720	2150
Subtotal		11402	13930	4000	8790	6200	5630	24620
Contingency (10%)		1140	1390	400	880	620	560	2460
TOTAL		12542	15320	4400	9670	6820	6190	27080

1) Assumes an average of 12 people during life of construction project. (Not included in original estimate.)

2) Actual escalation to 1978, assumed 10% per year 1978

3) Burden is the estimated extra cost because of stretched out funding (smaller contracts, in and out costs, etc.).

APPENDIX 2. PROJECT MANAGEMENT

PHASE I, 1981 DETAILED DESIGN

AUI/NRAO

Responsibilities:

- Develop performance specifications with limiting physical parameters.
- Develop conceptual plans and specifications.
- Contract with design firms.
- Supervise, review and approve preparation of construction drawings and specifications.

Personnel:

- Includes project management, scientific advisors, contracts, engineering, and fiscal.

CONTRACTORS

Nature of Contracts:

- One each for design of the telescope, design of the astrodome, and design of the site utilities and buildings.

Responsibilities:

- Detail design and preparation of construction drawings, specifications and contract documents in preparation for bidding.

PHASE II, 1982 PLAN A

AUI/NRAO

Responsibilities:	- Contract with construction firms.
	- Continually review and approve manufacturing, assembly and construction of each facility for conformance to contract drawings and specifications.
	- Observe final tests for conformance to performance specifications.
	- Coordinate between major contractors.
Personnel:	- Includes project management, contracts, engineering and fiscal.

CONTRACTORS

Nature of Contracts:	- One each for the telescope, astrodome and site utilities and buildings.
Responsibilities:	- Complete management of the construction for each major facility contracted, including purchasing, scheduling construction, and awarding of all subcontracts for manufacturing, assembly and construction as required by the particular contractor's facilities and capabilities, in conformance with the contract documents.

PHASE II, 1982 AND SUBSEQUENT YEARS: PLANS B, C

AUI/NRAO

Responsibilities:

- Function as general contractor during construction.
- Contract with all contractors and subcontractors.
- Purchase all material and equipment.
- Continually review and approve the manufacture, assembly, and construction of each facility for conformance to contract drawings and specifications.
- Observe final tests for conformance to performance specifications.
- Coordinate between all contractors.

Personnel:

- Includes project management, contracts, engineering, fiscal, and purchasing.

CONTRACTORS

Nature of Contracts:

- Numerous contracts and purchases for each of the telescope, astrodome, and site utilities and buildings.

APPENDIX 3

ANNUAL RECURRING EXPENSES
(in thousands of dollars)

Category	1979 Kitt Peak, 36-ft Actual	25-m Telescope Estimate in 1979$	in 1985*
Personnel Level	25	27	27
Salaries and Wages	$475	$595	$892
Premium for Hawaii[1]	-	65	97
Personnel Benefits	119	165	248
Travel	35	55	83
Freight	7	45	68
Vehicles	23	50	75
Communications & Utilities	40	300	450
Building Rent	31	31	47
Electronic Supplies	222	300	450
Other Material, Supplies & Services	199	199	298
Shared Services at the Site	-	37	55
Shared Services at Midlevel	-	58	87
Subtotal	1151	1900	2850
Other Potential Costs			
Fee for Land Use (U. of H.)[2]	-	?	?
Relocation[3]		72	108
Tuition Assistance[4]		40	60
Altitude Allowance[5]		18	27
Subtotal		130	195
TOTAL OPERATIONS	1151	2030	3045

* Costs projected to 1985 from 1979, assuming annual escalation of 7%.

APPENDIX 3

Notes to the Table:

[1] Allowance applied to mainland employees relocated to the Island of Hawaii (Federal allowance 15%).

[2] Fee for the use of the land at the telescope site. This has yet to be negotiated with the University of Hawaii.

[3] Cost of relocating employees having term appointments at the Hawaii facility.

[4] Cost of providing assistance for the education of employees' children.

[5] Premium pay for working at the high altitude site.

APPENDIX 4

These schedules are developed using the PERT technique. Schedules A3, B2 and C2 correspond to the funding plans A, B, C, respectively, described in Appendix 1.

Expected project completion dates are:

Plan A:	30 March 1984
Plan B:	22 May 1984
Plan C:	24 May 1985

```
                                        NATIONAL RADIO ASTRONOMY OBSERVATORY
                                                  ACTIVITY BAR CHART                                                          PAGE  1

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                                 25M001                          RUN DATE   03APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT                         MM0025      Plan A3

-----------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC    CY                           .      A - ACTIVITY COMPLETE                    P - PACING ITEM             .FINAL
EVENT EVENT   CD  DESCRIPTION              .      * - ACTIVITY DURATION                    - - ACTIVITY FLOAT          .DATE    DEPT
-----------------------------------------------------------------------------------------------------------------------------------
                                         .

25000 25010   AA DESIGN TELESCOPE        . :         .           PPPPPPPPPP  .           .           .           .     27OCT81
25021 25060   AA GET PANELS              . :         .           .           ***************----     .           .     07MAR83
25022 25080   AA GET FEED SUPPORT        . :         .           .           ********--------------  .           .     04AUG82
25023 25100   AA GET SUBREFLECTOR        . :         .           .           ************----------- .           .     24DEC82
25024 25120   AA GET BACK-UP SYSTEM      . :         .           .           *********---.           .           .     09SEP82
25025 25180   AA GET TOWER               . :         .           .           ******----  .           .           .     30JUN82
25026 25200   AA GET SERVO               . :         .           .           ***********---------    .           .     14OCT82
25030 25035   AA GET SURFACE PLATES PH 1 . :         .           .        PPP.           .           .           .     23DEC81
25035 25040   AA GET SURFACE PLATES PH 2 . :         .           .          PPPPPPPPPPPPPPPPPPPPPP   .           .     07SEP83
25040 25050   AA INSTALL SURAFACE PLATES . :         .           .           .           .       PP  .           .     19OCT83
25060 25070   AA INSTALL PANELS          . :         .           .           .           .    ***-   .           .     23AUG83
25080 25090   AA INSTALL FEED SUPPORT    . :         .           .           .           .        PP .           .     02NOV83
25100 25110   AA INSTALL SUBREFLECTOR    . :         .           .           .           .         P .           .     09NOV83
25120 25130   AA INSTALL BACK-UP SYSTEM  . :         .           .           .         ********-     .           .     27JUN83
25140 25150   AA GET FOUNDATION          . :         .           .           *****--     .           .           .     26MAY82
25160 25170   AA CONSTRUCT FOUNDATION    . :         .           .           .     ***-  .           .           .     29SEP82
25180 25190   AA INSTALL TOWER           . :         .           .           .       ***-.           .           .     24NOV82
25200 25210   AA INSTALL SERVO           . :         .           .           .           .    ****-- .           .     07SEP83
25220 25230   AA GET CONTROL COMPUTER    . :         .           .           *********-------------  .           .     16SEP82
25230 25240   AA INSTALL COMPUTER        . :         .           .           .       **------------- .           .     21OCT82
25250 25260   AA FINISH TELESCOPE        . :         .           .           .           .         PPP           .     19JAN84

25270 25280   BA DESIGN ASTRODOME        . :         .           ************.           .           .           .     23DEC81
25290 25300   BA GET ASTRODOME FOUNDATION. :         .           .           *****--     .           .           .     26MAY82
25310 25320   BA CONSTRUCT FOUNDATION    . :         .           .           .     ***-------        .           .     22SEP82
25330 25335   BA GET STRUC & DRIVE PH 1  . :         .           .          *****        .           .           .     20APR82
25335 25340   BA GET STRUC & DRIVE PH 2  . :         .           .           .  *************        .           .     01APR83
25340 25350   BA CONSTRUCT STRUCTURE     . :         .           .           .           .  ****     .           .     19JUL83
25360 25370   BA GET DOOR & DRIVE        . :         .           .           ***********--------     .           .     18NOV82
25370 25390   BA CONSTRUCT DOOR          . :         .           .           .           .     ***** .           .     02NOV83
25390 25400   BA GET AIR HANDLING        . :         .           .           ******----------------  .           .     23JUN82
25400 25410   BA CONSTRUCT AIR HANDLING  . :         .           .           .           .     ***---.           .     14SEP83
25420 25430   BA FINISH ASTRODOME        . :         .           .           .           .         **-           .     15DEC83

25440 25450   CA DESIGN SITE BUILDINGS   . :         .           ************.           .           .           .     09DEC81
25460 25465   CA GET ACCESS ROADS PH 1   . :         .           .          *****        .           .           .     06APR82
25465 25470   CA GET ACCESS ROADS PH 2   . :         .           .           .  ***      .           .           .     08JUN82
25470 25480   CA CONSTRUCT ACCESS ROADS  . :         .           .           .    **     .           .           .     13JUL82
25490 25495   CA GET GRADING, WASTE PH 1 . :         .           .          *****        .           .           .     06APR82
25495 25500   CA GET GRADING, WASTE PH 2 . :         .           .           .  ***      .           .           .     08JUN82
25500 25510   CA CONSTRUCT GRADING, ETC. . :         .           .           .    **     .           .           .     13JUL82
25520 25525   CA GET WATER SYSTEM PH 1   . :         .           .          *****        .           .           .     06APR82
25525 25530   CA GET WATER SYSTEM PH 2   . :         .           .           .  ***      .           .           .     08JUN82
25530 25540   CA CONSTRUCT WATER SYSTEM  . :         .           .           .    **     .           .           .     13JUL82
25560 25570   CA GET ELECTRICAL SYSTEM   . :         .           .           ******------------      .           .     30JUN82
25570 25580   CA CONSTRUCT ELECTRICAL SYS. :         .           .           .     *******-----------.           .     13JAN83
25590 25600   CA GET BUILDINGS           . :         .           .           ******-----------       .           .     30JUN82
25600 25610   CA CONSTRUCT BUILDINGS     . :         .           .           .     ********----------.           .     10FEB83
25620 25630   CA GET OTHER EQUIPMENT     . :         .           .           ******--------------    .           .     30JUN82
25630 25640   CA INSTALL OTHER EQUIPMENT . :         .           .           .     ****--------------.           .     27OCT82
                                               01JAN80     01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

```
                                       NATIONAL RADIO ASTRONCMY OBSERVATCRY
                                                 ACTIVITY BAR CHART                                                   PAGE  2

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                      25M001                         RUN DATE  03APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT              MM0025

---------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC    CY                         .      A - ACTIVITY COMPLETE                   P - PACING ITEM              .FINAL
FVENT EVENT   CD  DESCRIPTICN            .      * - ACTIVITY DURATION                   - - ACTIVITY FLOAT           .DATE   DEPT
---------------------------------------------------------------------------------------------------------------------------------
                                         .
2565C 25660   CA FINISH SITE             . :        .           .           .          .**----------          .    25MAR83

25700 END25   DA TEST SYSTEM             . :        .           .           .          .           PPP        .    30MAR84
                                               01JAN80    01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

```
                                        NATIONAL RADIO ASTRONOMY OBSERVATORY
                                                  ACTIVITY BAR CHART                                                         PAGE  1

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                      25M001                                RUN DATE  01APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT              MM0025    Plan B2

-----------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC    CY                                .      A - ACTIVITY COMPLETE                    P - PACING ITEM               .FINAL
EVENT EVENT   CD  DESCRIPTION                   .      * - ACTIVITY DURATION                    - - ACTIVITY FLOAT            .DATE    DEPT
-----------------------------------------------------------------------------------------------------------------------------------

                                         .

25000 25010   AA DESIGN TELESCOPE        . :         .           **********--.           .           .           .    27OCT81
25021 25060   AA GET PANELS              . :         .           .           ***************------   .           .    07MAR83
25022 25080   AA GET FEED SUPPORT        . :         .           .           .           ********----.           .    04AUG83
25023 25100   AA GET SUBREFLECTOR        . :         .           .           .           PPPPPPPPPPPP.           .    26DEC83
25024 25120   AA GET BACK-UP SYSTEM      . :         .           .           *********----           .           .    09SEP82
25025 25180   AA GET TOWER               . :         .           .           ******------.           .           .    30JUN82
25026 25200   AA GET SERVO               . :         .           .           .           **********  .           .    14OCT83
25030 25035   AA GET SURFACE PLATES PH 1 . :         .                    ***--          .           .           .    23DEC81
25035 25040   AA GET SURFACE PLATES PH 2 . :         .           .          *********************-   .           .    07SEP83
25040 25050   AA INSTALL SURAFACE PLATES . :         .           .           .           .       **--.           .    19OCT83
25060 25070   AA INSTALL PANELS          . :         .           .           .           .    ***--  .           .    23AUG83
25080 25090   AA INSTALL FEED SUPPORT    . :         .           .           .           .        **-.           .    02NOV83
25100 25110   AA INSTALL SUBREFLECTOR    . :         .           .           .           .          PP           .    02JAN84
25120 25130   AA INSTALL BACK-UP SYSTEM  . :         .           .           .         ********---   .           .    27JUN83
25140 25150   AA GET FOUNDATION          . :         .           .           *****----   .           .           .    26MAY82
25160 25170   AA CONSTRUCT FOUNDATION    . :         .           .           .     ***---.           .           .    29SEP82
25180 25190   AA INSTALL TOWER           . :         .           .           .       ***--           .           .    24NOV82
25200 25210   AA INSTALL SERVO           . :         .           .           .           .        ***-           .    26DEC83
25220 25230   AA GET CONTROL COMPUTER    . :         .           .           .           *********-- .           .    16SEP83
25230 25240   AA INSTALL COMPUTER        . :         .           .           .           .       **---           .    21OCT83
25250 25260   AA FINISH TELESCOPE        . :         .           .           .           .           PPP         .    13MAR84

25270 25280   BA DESIGN ASTRODOME        . :         .           *************--         .           .           .    23DEC81
25290 25300   BA GET ASTRODOME FOUNDATION. :         .           .           *****----   .           .           .    26MAY82
25310 25320   BA CONSTRUCT FOUNDATION    . :         .           .           .     ***---------      .           .    22SEP82
25330 25335   BA GET STRUC & DRIVE PH 1  . :         .           .          *****--      .           .           .    20APR82
25335 25340   BA GET STRUC & DRIVE PH 2  . :         .           .           .  *************--      .           .    01APR83
25340 25350   BA CONSTRUCT STRUCTURE     . :         .           .           .           .  ****--   .           .    19JUL83
25360 25370   BA GET DOOR & DRIVE        . :         .           .           ***********----------   .           .    18NOV82
25370 25380   BA CONSTRUCT DOOR          . :         .           .           .           .     *****--           .    02NOV83
25390 25400   BA GET AIR HANDLING        . :         .           .           .           ******------.           .    22JUN83
25400 25410   BA CONSTRUCT AIR HANDLING  . :         .           .           .           .     ***----           .    14SEP83
25420 25430   BA FINISH ASTRODOME        . :         .           .           .           .         **---         .    15DEC83

25440 25450   CA DESIGN SITE BUILDINGS   . :         .           *************--         .           .           .    09DEC81
25460 25465   CA GET ACCESS ROADS PH 1   . :         .           .          *****--      .           .           .    06APR82
25465 25470   CA GET ACCESS ROADS PH 2   . :         .           .           .  ***--    .           .           .    08JUN82
25470 25490   CA CONSTRUCT ACCESS ROADS  . :         .           .           .    **--   .           .           .    13JUL82
25490 25495   CA GET GRADING, WASTE PH 1 . :         .           .          *****--      .           .           .    06APR82
25495 25500   CA GET GRADING, WASTE PH 2 . :         .           .           .  ***--    .           .           .    08JUN82
25500 25510   CA CONSTRUCT GRADING, ETC. . :         .           .           .    **--   .           .           .    13JUL82
25520 25525   CA GET WATER SYSTEM PH 1   . :         .           .          *****--      .           .           .    06APR82
25525 25530   CA GET WATER SYSTEM PH 2   . :         .           .           .  ***--    .           .           .    08JUN82
25530 25540   CA CONSTRUCT WATER SYSTEM  . :         .           .           .    **--   .           .           .    13JUL82
25560 25570   CA GET ELECTRICAL SYSTEM   . :         .           .           ******-------------     .           .    30JUN82
25570 25590   CA CONSTRUCT ELECTRICAL SYS. :         .           .           .     *******------------           .    13JAN83
25590 25600   CA GET BUILDINGS           . :         .           .           .           PPPPPP      .           .    29JUN83
25600 25610   CA CONSTRUCT BUILDINGS     . :         .           .           .           .    PPPPPPPP           .    30JAN84
25620 25630   CA GET OTHER EQUIPMENT     . :         .           .           .           ******----  .           .    29JUN83
25630 25640   CA INSTALL OTHER EQUIPMENT . :         .           .           .           .    *****---           .    14OCT83
                                               01JAN80     01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

```
                                        NATIONAL RADIO ASTRONOMY OBSERVATORY
                                                  ACTIVITY BAR CHART                                                    PAGE 2

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                       25M001                          RUN DATE 01APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT                MM0025

-----------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC    CY                         .      A - ACTIVITY COMPLETE                    P - PACING ITEM              .FINAL
EVENT EVENT   CD  DESCRIPTION            .      * - ACTIVITY DURATION                    - - ACTIVITY FLOAT           .DATE    DEPT
-----------------------------------------------------------------------------------------------------------------------------------
                                         .
25650 25660   CA FINISH SITE             . :         .           .           .           .           PPP         .     13MAR84

25700 END25   DA TEST SYSTEM             . :         .           .           .           .           . PPP       .     22MAY84
                                               01JAN80     01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

```
                                        NATIONAL RADIO ASTRONOMY OBSERVATORY
                                                  ACTIVITY BAR CHART                                                   PAGE  1

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                       25M001                         RUN DATE [redacted]APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT               MM0025     Plan C2


----------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC    CY                         .      A - ACTIVITY COMPLETE                    P - PACING ITEM              .FINAL
EVENT EVENT   CD  DESCRIPTION            .      * - ACTIVITY DURATION                    - - ACTIVITY FLOAT           .DATE   DEPT
----------------------------------------------------------------------------------------------------------------------------------

                                         .

25000 25010   AA DESIGN TELESCOPE        . :         .           **********--------------.           .           .     27OCT81
25021 25060   AA GET PANELS              . :         .           .           .           ***************------   .     06MAR84
25022 25080   AA GET FEED SUPPORT        . :         .           .           .           ********----------------.     04AUG83
25023 25100   AA GET SUBREFLECTOR        . :         .           .           .           ************------------.     26DEC83
25024 25120   AA GET BACK-UP SYSTEM      . :         .           .           .           *********----           .     09SEP83
25025 25180   AA GET TOWER               . :         .           .           .           ******------.           .     29JUN83
25026 25200   AA GET SERVO               . :         .           .           .           **********------------  .     14OCT83
25030 25035   AA GET SURFACE PLATES PH 1 . :         .           .        ***--------------          .           .     23DEC81
25035 25040   AA GET SURFACE PLATES PH 2 . :         .           .          **********************-------------  .     07SEP83
25040 25050   AA INSTALL SURAFACE PLATES . :         .           .           .           .           .    **-----.     19JUL84
25060 25070   AA INSTALL PANELS          . :         .           .           .           .           .  ***----  .     06JUN84
25080 25090   AA INSTALL FEED SUPPORT    . :         .           .           .           .           .     **----.     02AUG84
25100 25110   AA INSTALL SUBREFLECTOR    . :         .           .           .           .           .      *-----     09AUG84
25120 25130   AA INSTALL BACK-UP SYSTEM  . :         .           .           .           .       ********----    .     10APR84
25140 25150   AA GET FOUNDATION          . :         .           .           *****----------------   .           .     26MAY82
25160 25170   AA CONSTRUCT FOUNDATION    . :         .           .           .     ***---------------.           .     29SEP82
25180 25190   AA INSTALL TOWER           . :         .           .           .           .    ***-----           .     25AUG83
25200 25210   AA INSTALL SERVO           . :         .           .           .           .           .  ***-------     20JUN84
25220 25230   AA GET CONTROL COMPUTER    . :         .           .           .           .           *********-- .     14SEP84
25230 25240   AA INSTALL COMPUTER        . :         .           .           .           .           .       **---     19OCT84
25250 25260   AA FINISH TELESCOPE        . :         .           .           .           .           .        ****--   02JAN85

25270 25280   BA DESIGN ASTRODOME        . :         .           ************--------------          .           .     23DEC81
25290 25300   BA GET ASTRODOME FOUNDATION. :         .           .           *****----------------   .           .     26MAY82
25310 25320   BA CONSTRUCT FOUNDATION    . :         .           .           .     ***--------------------       .     22SEP82
25330 25335   BA GET STRUC & DRIVE PH 1  . :         .           .          *****--------------      .           .     20APR82
25335 25340   BA GET STRUC & DRIVE PH 2  . :         .           .           .  *************-------------       .     01APR83
25340 25350   BA CONSTRUCT STRUCTURE     . :         .           .           .           .  ****--------------   .     19JUL83
25360 25370   BA GET DOOR & DRIVE        . :         .           .           ***********----------------------   .     18NOV82
25370 25380   BA CONSTRUCT DOOR          . :         .           .           .           .     *****--------------     02NOV83
25390 25400   BA GET AIR HANDLING        . :         .           .           .           .           ******------.     20JUN84
25400 25410   BA CONSTRUCT AIR HANDLING  . :         .           .           .           .           .    ***-----     16AUG84
25420 25430   BA FINISH ASTRODOME        . :         .           .           .           .           .      **------   28SEP84

25440 25450   CA DESIGN SITE BUILDINGS   . :         .           ************--------------          .           .     09DEC81
25460 25465   CA GET ACCESS ROADS PH 1   . :         .           .          *****--------------      .           .     06APR82
25465 25470   CA GET ACCESS ROADS PH 2   . :         .           .           .  ***--------------    .           .     08JUN82
25470 25480   CA CONSTRUCT ACCESS ROADS  . :         .           .           .    **--------------   .           .     13JUL82
25490 25495   CA GET GRADING, WASTE PH 1 . :         .           .          *****----------------    .           .     06APR82
25495 25500   CA GET GRADING, WASTE PH 2 . :         .           .           .  ***--------------    .           .     08JUN82
25500 25510   CA CONSTRUCT GRADING, ETC. . :         .           .           .    **--------------   .           .     13JUL82
25520 25525   CA GET WATER SYSTEM PH 1   . :         .           .          *****--------------      .           .     06APR82
25525 25530   CA GET WATER SYSTEM PH 2   . :         .           .           .  ***--------------    .           .     08JUN82
25530 25540   CA CONSTRUCT WATER SYSTEM  . :         .           .           .    **--------------   .           .     13JUL82
25560 25570   CA GET ELECTRICAL SYSTEM   . :         .           .           ******-------------------------     .     30JUN82
25570 25580   CA CONSTRUCT ELECTRICAL SYS. :         .           .           .     *******------------------------     13JAN83
25590 25600   CA GET BUILDINGS           . :         .           .           .           .           PPPPPP      .     27JUN84
25600 25610   CA CONSTRUCT BUILDINGS     . :         .           .           .           .           .    PPPPPPPP     30JAN85
25620 25630   CA GET OTHER EQUIPMENT     . :         .           .           .           .           ******----  .     27JUN84
25630 25640   CA INSTALL OTHER EQUIPMENT . :         .           .           .           .           .    *****---     12OCT84
                                               01JAN80     01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

```
                                        NATIONAL RADIO ASTRONOMY OBSERVATORY
                                                  ACTIVITY BAR CHART                                                     PAGE  2

PROGRAM      20MAR79   REPORT DATE.  25M TELESCOPE PROJECT                     25M001                         RUN DATE  01APR79
PROJECT             25M SITE, TELESCOPE AND ASTRODOME  DEVELOPMENT             MM0025


--------------------------------------------------------------------------------------------------------------------------------
PRED  SUCC   CY                           .      A - ACTIVITY COMPLETE                P - PACING ITEM             .FINAL
EVENT EVENT  CD  DESCRIPTION              .      * - ACTIVITY DURATION                - - ACTIVITY FLOAT          .DATE    DEPT
--------------------------------------------------------------------------------------------------------------------------------
                                          .
2565C 25660  CA FINISH SITE               . :         .           .           .           .           .          PPP   15MAR85

25700 END25  DA TEST SYSTEM               . :         .           .           .           .           .          . PPP 24MAY85
                                               01JAN80     01JAN81     01JAN82     01JAN83     01JAN84     01JAN85
```

Chemical &
Engineering
NEWS

Chemistry of Interstellar Space

Richard H. Gammon

Reprinted from Chemical & Engineering News, Vol. 56, October 2, 1978, pages 21–33

Chemistry of Interstellar Space

Richard H. Gammon, Pacific Science Center and University of Washington

Our sun is a typical star, one of the estimated 200 billion comprising the luminous bulk of our galaxy, the Milky Way. Ninety per cent of the galactic mass is currently in the condensed form of such glowing stars; the rest is scattered nonuniformly throughout the dark reaches of interstellar space. This interstellar matter is a very tenuous gas, mostly hydrogen and helium, with just a sprinkling of heavier elements collected in grains of stardust. The stardust is the result of nucleosynthesis in, and mass loss from, earlier generations of stars. These dust grains, about 0.1 micrometer in size, are of uncertain composition. They are only 10^{-12} as abundant as hydrogen. Although quite rare, these dust grains play a critical role in the creation and destruction of interstellar molecules.

The young, hot stars of our galaxy outline a thin, differentially spinning galactic disk. Shaped like a giant phonograph record, the Milky Way measures roughly 100,000 light years across but is less than 2000 light years thick. Our sun is in the galactic suburbs, about two thirds of the way out from the galactic center, which it orbits once every 200 million years. The interstellar matter forms an even thinner disk than do the stars; the galactic disk, as defined by the radio emission from carbon monoxide, has been measured recently to be less than 300 light years thick. Older generations of cool stars, which are poor in elements heavier than helium, are found in two different parts of the galaxy: the nuclear bulge at the center of the Milky Way's spinning disk and an extended swarm of clumped old stars (globular clusters) which surround it in a spherical halo. The extent of this halo probably represents the dimensions of the pregalactic gas cloud which collapsed some 10 billion to 15 billion years ago to form our present galaxy. With the exception of the two giant molecular clouds of the constellation Sagittarius, which are located in the galactic center, this discussion of interstellar chemistry will focus on the ragged patches of interstellar gas and dust between the stars in the galactic plane. Averaged over the galaxy, the distance between stars is a few light years, whereas the distance between hydrogen atoms in the interstellar gas is on the order of a centimeter.

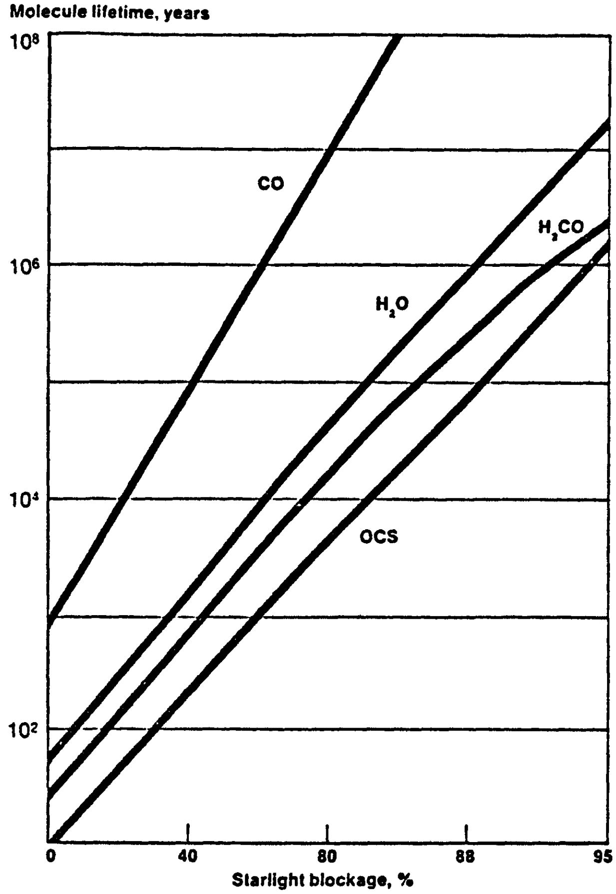
Largely through galactic mapping of the characteristic radio emission of hydrogen atoms at a wave length of 21 cm, astronomers have begun to sketch the arms of a spiral pattern in the Milky Way. In other spiral galaxies, these arms are visibly outlined by three indicators of active star formation—hot, young, massive stars; regions of dense, ionized gas; and lanes of stardust. The density of matter in the region of a spiral arm may be three to 10 times higher than in the interarm regions. The origin and persistence of the spiral pattern, and its relationship to the process of star formation on a galactic scale, are currently subjects of great theoretical and experimental interest.

In the standard, steady-state model, interstellar space is sharply divided into two phases in pressure equilibrium. A cool (100° K), dense "cloud" phase containing about 10 hydrogen atoms per cc is immersed in a hotter (10,000° K) more tenuous "intercloud" phase that contains only 0.1 hydrogen atom per cc.

Recent ultraviolet observations from the orbiting Copernicus satellite of highly ionized interstellar atomic oxygen (O^{+5}) have led to time-dependent models of an even hotter (100,000° to 1 million degrees K), thinner (0.01 to 0.001 hydrogen atom per cc) third phase in interstellar space. Interstellar space in one such model is likened to a vast, tangled spaghetti of interconnecting tubes and bubbles, generated and maintained by blast waves of successive supernova explosions.

The cool, dense "cloud" phase, which occupies less than 10% of interstellar volume, is the only possible site for chemical evolution, apart from the atmospheres of planets and cool stars. The relative abundances of the elements available in these clouds for the formation of molecules have been determined by

Exposure to starlight limits the life of interstellar molecules



The lifetime of molecules in interstellar space before they are destroyed by diffuse ultraviolet starlight. If unshielded, most molecules will survive less than 100 years. In a dark dust cloud of moderate density, where 95% of the starlight is blocked by cosmic dust grains, molecules may last more than 1 million years. Carbon monoxide, a molecule abundant in clouds, has an unusually long lifetime.

analysis of solar and stellar spectra, combined with studies of the compositon of terrestrial, lunar, and meteoritic materials. Interstellar molecules containing hydrogen, nitrogen, carbon, oxygen, sulfur, and silicon have already been observed. Searches for species containing iron, magnesium, aluminum, calcium, chlorine, and phosphorus have not yet been successful. Optical and ultraviolet atomic spectroscopy of the nearby interstellar gas, that within a distance of 3000 light years from earth, shows that most elements heavier than helium seem less abundant or depleted in interstellar clouds relative to their total cosmic abundance. This depletion ranges from a third to a tenth the expected value for such elements as carbon, nitrogen, oxygen, sulfur, and silicon to less than a hundredth the expected abundance for aluminum and titanium.

Where is this missing material? A small fraction of the lighter and more volatile elements is certainly in molecular form, particularly in the denser, darker clouds. The major sink, however, is thought to be the interstellar dust grains, which collide with and gather up heavy atoms from the gas. This idea was given a quantitative expression in the "condensation-accretion" model of George Field of the Center for Astrophysics at Harvard University, who demonstrated a correlation between the observed elemental depletion and the equilibrium condensation temperature of minerals containing those elements at temperatures from 1600° K down to 500° K.

Radio observations of interstellar molecules within dark dust clouds, which are inacessible to optical and ultraviolet spectroscopy, now allow the determination of elemental and is topic abundances throughout our galaxy. This opens the fascinating possibility of tracing the chemical history of stellar nucleosynthesis since our galaxy formed 10 billion to 15 billion years ago out of a nearly pure gas of primordial hydrogen and helium. All the heavier elements were formed subsequently by nuclear fusion reactions in the cores of massive stars, and then returned to interstellar space, either wafted away from red giant stars by stellar winds or blasted out by violent, star-destroying supernova explosions. These heavy elements, which were required for the evolution of life on earth, were formed in the dying stage of earlier generations of stars before the sun lit up 4.5 billion years ago. The repeated cycling of interstellar matter through stars every few hundred million years has been gradually enriching the interstellar gas with such elements, the products of star-burning reactions fueled by the primordial hydrogen and helium.

The nature of the chemistry in interstellar clouds depends not only on the abundance of the various elements, but even more strongly on the content and forms of energy available within the clouds to promote chemical reactions. These energy forms include diffuse starlight impinging on the cloud surface; internal kinetic energy, including systematic motions and turbulence; gravitational self-energy; energy associated with the interstellar magnetic field; energy of chemical reactions; the influx of galactic cosmic rays and x-rays; and the 3° K cosmic microwave background radiation.

Energy sources in interstellar clouds

The most important energy source in the more transparen interstellar clouds is the diffuse galactic starlight, which is composite of the light from all the stars within a distance of a few thousand light years from the cloud. It is dominated by light from luminous young stars that have a temperature of 10,000° K or more. The peak energy density of the light from these young stars is in the wave-length range of 1000 to 2000 A. Such ultraviolet photons have sufficient energy to ionize atoms and break chemical bonds. The ultraviolet absorption of atomic hydrogen itself limits this spectrum of interstellar photons to wave lengths greater than 912 A. This means that, in diffuse clouds, elements like carbon, which can be ionized at lower photon energies than hydrogen, will exist primarily in ionized form, whereas elements such as nitrogen and oxygen with ionization potentials higher than that of atomic hydrogen, which has an ionization potential of 13.6 eV, will remain neutral. Most molecular species are photodissociated or photoionized by this diffuse starlight at even lower energies than are the elemental atoms. Photolifetimes are less than 100 years for interstellar molecules directly exposed to the diffuse galactic starlight, but increase to more than 1 million years for molecules sequestered deep within the dark dust clouds where less than 5% of this starlight penetrates.

The internal kinetic energy of molecular clouds, most recently determined by the radio intensity of the rotational transitions of interstellar carbon monoxide, varies from kinetic temperatures as low as 10° K for clouds in which the density of hydrogen is about 1000 to 10,000 molecules per cc to temperatures exceeding 100° K at the cores of denser clouds containing about 1 million hydrogen molecules per cc and imbedded infrared hot spots. Detailed studies of molecular line shapes have indicated systematic motions within dark clouds, although the extent t which this is a result of collapse (or expansion) or of rotation and turbulence is still being hotly debated.

Most interstellar clouds in which molecules have been observed are considered to be gravitationally bound and certain to collapse to form new stars. This collapse may be hindered by the rotational angular momentum of the cloud or by the presence of magnetic fields, which typically have strengths of just a few microgauss, or about 100,000 times weaker than that of the earth.

In the denser dust clouds, from which ultraviolet starlight is excluded, the primary energy input is thought to be ionization due to the influx of soft x-rays (100 eV) and galactic cosmic rays (1 to 100 MeV per nucleon). The ionization rate deep within the cloud due to x-rays and cosmic rays is only a tenth to a hundredth that of 10^{-15} per hydrogen atom per second that is caused by starlight at the surface of the cloud, but still is considered sufficient to drive the chemical reactions observed there.

The most important chemical energy source in the dense clouds is the association of hydrogen atoms to form diatomic hydrogen molecules on grain surfaces, which releases 4 eV for each molecule formed.

The ubiquitous cosmic microwave background radiation is considered to be the red-shifted remnant of the primordial fireball with which the "big bang" universe began. With an energy density similar to that of the diffuse starlight (10^{-12} erg per cc), this radiation presents a black-body spectrum with peak brightness at a wave length of approximately 1 mm, corresponding to a temperature of 2.7° K. This is then the lowest physical temperature possible. This radiation is not important in determining the nature of the interstellar chemistry, but is crucial in determining the relative populations of the lowest energy levels of interstellar molecules, and therefore in understanding their excitation and abundance in interstellar clouds. For example, the interstellar optical absorption spectrum of the cyanide radical, one of the first three interstellar species detected nearly 40 years ago, indicates a temperature near 3° K. This puzzling result was observed decades before the big-bang cosmology became generally accepted with the direct detection of the cosmic 3° K background radiation in 1965 by Arno Penzias and Robert Wilson of Bell Telephone Laboratories.

In comparing the properties of dark and black molecular clouds, it is well to point out that this division is somewhat arbitrary. Clouds have a continuous range of densities, sizes, and other properties. Certain generalizations apply, however, to all interstellar clouds in which molecules have been observed. All interstellar clouds are cold (temperatures are 100° K or less), weakly ionized (fewer than one hydrogen atom in 10,000 is ionized), and hydrogen-rich.

The most diffuse clouds have been studied using optical and ultraviolet radiation because they are at least partly transparent at these wave lengths. The ionization and thermal balance in these diffuse clouds is controlled by penetrating starlight. Typical temperatures of such clouds are about 100° K, and gas densities range from 10 to 100 hydrogen atoms per cc. The hydrogen is overwhelmingly in atomic form. And molecules there are limited to a low concentration of diatomic species such as CH, CH^+, CN, CO, and OH. Diffuse clouds are, in general, not gravitationally bound, which means they will eventually evaporate, returning to the intercloud medium without ever collapsing to form new stars.

Hydrogen is by far the most common element in interstellar space

Cosmic abundances of the most common elements, relative to hydrogen

H	1.00	Fe	4×10^{-5}	Ca	2×10^{-6}
He	0.09	Si	3×10^{-5}	Ni	2×10^{-6}
O	7×10^{-4}	Mg	3×10^{-5}	Na	2×10^{-6}
C	3×10^{-4}	S	2×10^{-5}	Cr	7×10^{-7}
N	9×10^{-5}	Ar	6×10^{-6}	Cl	4×10^{-7}
Ne	8×10^{-5}	Al	2×10^{-6}	P	3×10^{-7}

Dark and black molecular clouds have importantly contrasting properties

Property	"Dark" clouds	"Black" clouds
Transparence to starlight	Slightly translucent (≥1% transmission)	Opaque (≤1% transmission)
Size (light years)	3–150	3
Gas density (cm^{-3})	10^2–10^4	10^4–10^6
Hydrogen form	Atomic, molecular	Molecular
Kinetic temperature (°K)	10–20	30–100
Gravitationally bound	Usually	Always
Collapse times[a]	Usually 10^6 years	Always 10^5 years
Central condensation, infrared hotspots (protostars?)	Rarely	Often
Observed molecular species	Usually simpler, such as H_2, CO, H_2CO, HCN, HCO^+, HN_2^+, CN	Includes more complex polyatomics, such as $(CH_3)_2O$, CH_3CH_2CN
Steady-state chemistry	Likely	Less likely
Gas-phase or surface reactions dominant	Gas phase	?
Ionization (n_e/n_H)	$\leqslant 10^{-4}$	$\leqslant 10^{-8}$

[a] Estimated time required for a self-gravitating cloud to contract to stellar dimensions.

The dark and black clouds, on the other hand, have a range of density that is more accessible to radio than to optical astronomy. In the more tenuous clouds, hydrogen gas is overwhelmingly in atomic form; in the denser clouds the hydrogen is found in diatomic molecular form. Ultraviolet observations from the Copernicus observatory have confirmed previous theoretical predictions that the transition from clouds that essentially are composed of atomic hydrogen to clouds that are essentially molecular hydrogen occurs very abruptly when the density of both hydrogen atoms and molecules combined totals a few hundred per cc. The dark and black clouds are both molecular hydrogen clouds, and are certainly gravitationally bound. The sharp phase transition from atomic to molecular hydrogen with increasing cloud density is accompanied by a sharp decrease in the ionization resulting from ultraviolet starlight; the denser clouds become darker and colder. Another key transition that occurs with the same change in density is that of carbon from predominantly C^+ in atomic-hydrogen clouds to carbon monoxide in molecular-hydrogen clouds. Carbon monoxide is the second most abundant known interstellar molecule; the ratio of carbon monoxide to hydrogen molecules is about 3×10^{-5}, a value found to be surprisingly independent of cloud density. The variety of chemicals observed in these molecular hydrogen clouds is much richer than in the "diffuse" clouds. Stable polyatomic species (NH_3, H_2CO, HCN) are found, as well as several more exotic radicals and molecular ions not previously known as gas-phase species in laboratories on earth, such as HCO^+, HN_2^+, HCC, HNC, C_3N, and C_4H.

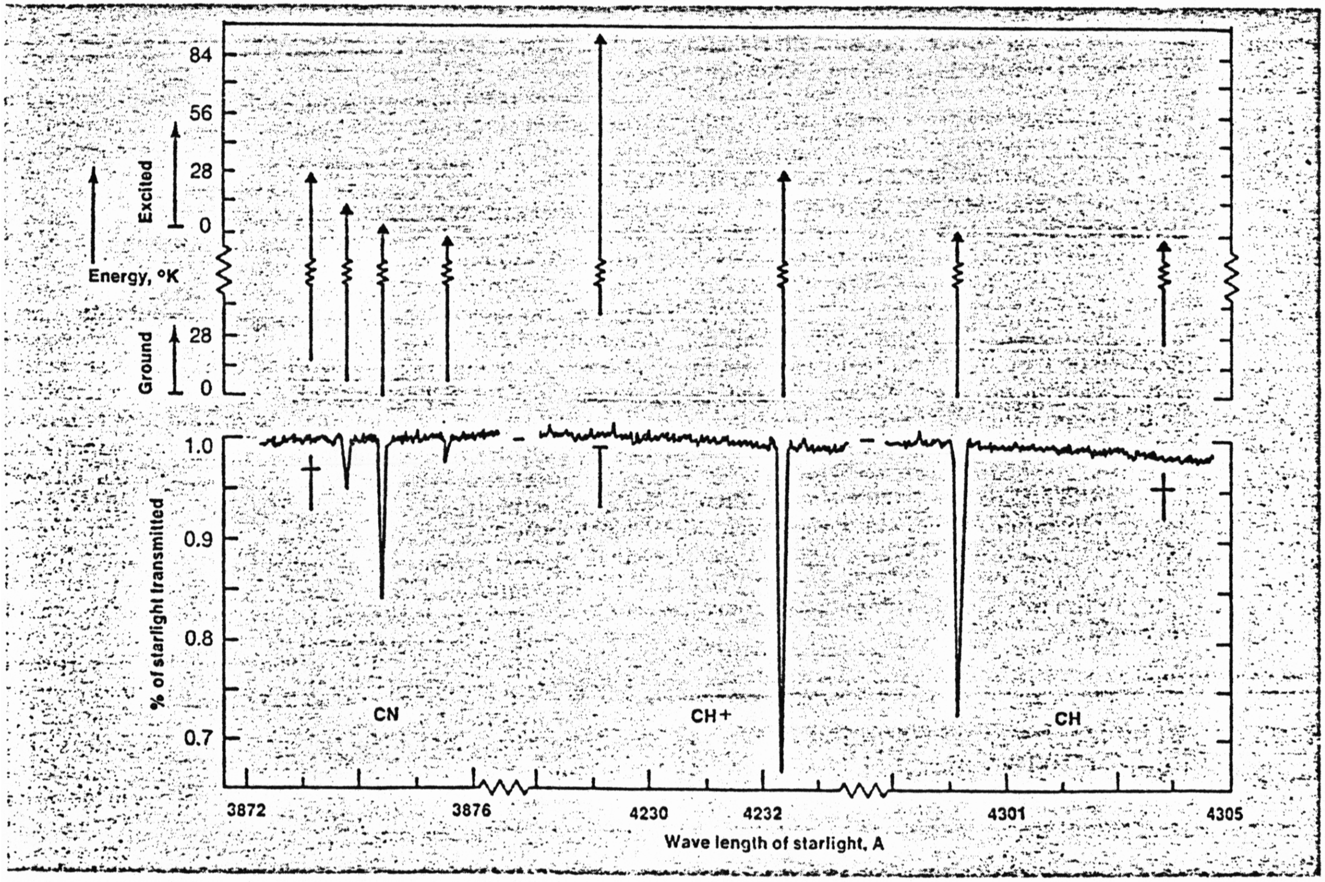
In the "dark" clouds, the time required to reach a chemical steady state is likely to be less than the time required for the gravitational collapse of the clouds. This means that chemical models based on the simplifying assumption of steady-state conditions probably are valid in such clouds, and that the chemical abundances can keep up with the evolving temperature and density of the infalling cloud. However, the influx of ionizing radiation of all kinds (ultraviolet, x-ray, and cosmic) drives the observed interstellar chemistry far from the expected products, such as methane, ammonia, and water, of thermodynamic equilibrium appropriate to the hydrogen-rich, low-temperature cloud environment.

The denser, more opaque clouds called "black" are really condensed regions within more extended dark clouds. Such black clouds are hotter, at least at the condensing cores, because they are heated first by gravitational collapse and eventually by the nuclear burning of the newborn star. Collapse is believed to be nonhomologous, that is, faster at the core than at the edges of the cloud. The higher densities and temperatures in "black" clouds stimulate a richer chemistry, or at least facilitate the excitation of more energetic transitions than those observed in dark clouds. The source of ionization in such clouds is less certain; it may include new stars embedded within the cloud itself. A further complication is the uncertain role of dust grains in the synthesis of the complex polyatomic species, such as dimethyl ether and ethyl alcohol, which have been observed in black clouds. Finally, there is the possibility that the time required for chemical reactions to reach steady-state conditions may be longer than the collapse time for such dense clouds. Two examples of such black clouds are the cores of the nearby (1200 light years away) Orion molecular cloud and the distant (30,000 light years away) galactic center source called Sagittarius B2. Nearly all interstellar species have been seen first in one or both of these black clouds and some have been found only in these sources. Such clouds are among the most massive objects in the galaxy, with a mass as much as 100,000 that of our sun, and are often intimately associated with prominent glowing volumes of ionized gas surrounding and produced by massive young stars.

The physical and chemical conditions in interstellar clouds are very different from those of terrestrial laboratories. The life of interstellar molecules unshielded from photodissociation [illegible] interstellar space is typically 100 years, but increases to about 1 million years in dust clouds of moderate opacity. This means that the photolifetime of molecules in such clouds may be as long as the life of the cloud itself. For example, a typical interstellar cloud collides supersonically with neighboring clouds every 10 million years. Collapse times for isolated clouds may be as short as 1 million years or less.

Gas-phase chemical reactions in interstellar clouds can occur only as rapidly as do atom-atom collisions, that is about once a year when the density of hydrogen is about 300 atoms per cc. Collisions of an atom with a grain of stardust are much less frequent, taking place only once in 100,000 years in a cloud of similar density. Of course not every collision leads to a reaction, but the observed chemistry is dominated by reactions that have large cross sections and no activation energy. In low-density clouds, the diatomic radiative association reaction (A + B → AB + photon) is very inefficient, with only one molecule formed in about 10 million collisions. However, this process is believed to dominate the formation of interstellar CH and CH^+. Reactions on grain surfaces are problematical because of uncertainties in the grain surface, atomic sticking probabilities, and surface mobilities. Surface reactions (A + B + grain → AB + grain) probably require a few million years in a cloud in which the density of hydrogen is about 300 atoms per cc.

Interstellar molecules absorb light from stars behind them



The interstellar optical absorption spectra of the three species first detected in interstellar space, as observed in nearby diffuse clouds against the light of bright background stars. Above each spectrum, the corresponding pattern of rotational energy levels for the ground and excited electronic states of each molecule is shown schematically. Crosses on the spectra mark the expected position of unobserved absorption lines from higher rotational states of the ground electronic state; the absence of such lines indicates that these molecules are at a temperature of about 3° K.

A very important time scale is that for three-body collisions. Under standard temperature and pressure conditions on earth, three-body collisions occur in about 10^{-8} second. In interstellar clouds, however, such collisions are completely negligible. Thus, no third body is ever available to stabilize the products of a gas-phase collision in interstellar clouds.

Finally, with regard to the collisional excitation of molecular energy levels vs. spontaneous emission of microwave photons in downward rotational transitions, the radiative lifetimes for allowed rotational transitions are typically days to years; such times are comparable to the atom-atom collision times for moderate cloud densities. So its's nip and tuck as collisions with hydrogen molecules pump interstellar molecules up to excited rotational levels about as rapidly as they spontaneously radiate down again.

Interstellar spectroscopy and excitation

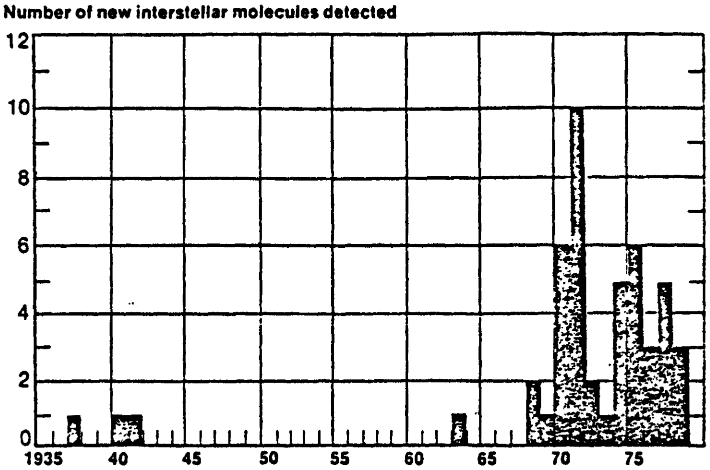
The radio detection of the OH radical in interstellar space in 1963, following the optical detection of the first three interstellar species by about a quarter of a century, seemed to confirm the notion that interstellar conditions were too harsh to permit more than simple, diatomic molecules to exist. The real richness of the interstellar chemistry has become apparent only in the past decade, beginning with radio detections of two stable, polyatomic species, water and ammonia, in 1968. The subsequent pace of discovery has averaged between four and five detections per year, so that as of last June the list of known interstellar molecules included some 50 species. These molecules have been first identified almost exclusively by their characteristic spectral lines at centimeter and millimeter (radio) wave lengths. Fishing has been particularly good in the 3-mm wave-length band with the unique high sensitivity and spectral resolution of the 11-m-diameter radio telescope on Kitt Peak, Ariz., operated by the National Radio Astronomy Observatory.

The following discussion will focus on the methods employed in identifying and interpreting interstellar spectral lines at radio wave lengths, although complementary studies at other wave lengths also have been productive. In particular, the ultraviolet observations of nearby translucent interstellar clouds from the Copernicus satellite are helping to define the nature of the interstellar chemistry where the density of hydrogen atoms is only 10 to 100 per cc. Also, the recent infrared detection of acetylene by astronomers at Kitt Peak promises new physical and chemical insight into protostellar regions, where density and temperature are higher than normally encountered by radio astronomers.

The reason radio astronomy has so dominated the study of interstellar molecules is simply that the spacing between the lowest molecular energy levels is comparable to the thermal energy available within dark interstellar clouds. With the prominent exceptions of atomic hydrogen and molecular hydrogen, interstellar molecules have been most often detected using electric-dipole transitions between rotational or fine-structure levels of the ground electronic, and usually the ground vibrational, state. Only species possessing a permanent electric dipole moment can exhibit such transitions. For this reason, several nonpolar, but presumably abundant, species, such as carbon dioxide, have so far eluded interstellar detection. It is likely that such "unobservable" interstellar species will eventually be identified by their infrared-active, vibration-rotation spectra, as was the case in the recent detection of interstellar acetylene.

The list of detected species includes a full range of molecular geometries—simple diatomics, linear polyatomics, symmetric tops, and asymmetric tops. At the longer radio wave lengths, the most important transitions observed have been of two types: transitions across the electronic-rotational fine structure in diatomic free radicals (OH, CH); and transitions between closely spaced rotational levels in asymmetric polyatomic species (H_2CO, HCOOH).

The pace of discovery of interstellar molecules has increased in the 1970's



Note: 1978 point based on first six months.

The initial three molecules (CN, CH, and CH+) observed in space were detected optically. More recent discoveries have been almos exclusively made at radio wave lengths and have averaged more than four new species a year during the past decade.

At the shorter radio wave lengths, interstellar radiation fields are weaker. Consequently, collisions with hydrogen molecules dominate the excitation of molecular rotational states. The most commonly observed transitions are spontaneous rotational emissions with typical radiative lifetimes of 10,000 to 1 million seconds.

The asymmetric polyatomic molecules have the added complexity of multiple components of the transition dipole moment, often compounded by the effects of nonrigidity. Hindered internal rotation of methyl groups (as is the case with methanol), inversion (ammonia), or both (methylamine) presents formidable problems for both laboratory and interstellar spectroscopists alike.

How are interstellar molecules identified? In most cases, at least for the simpler and more stable species, the laboratory microwave spectroscopy is completed before the interstellar search is made. Identification generally rests on precise (1 part in 10^5) agreement of laboratory and interstellar transition frequencies, corrected for Doppler shifts due to the line-of-sight velocity of the interstellar cloud (typically 1 part in 10^4). Confirming observations of additional transitions, or of the same transition in an isotopically substituted species, are required for the general acceptance of a new identification.

More exotic molecules, for which no frequencies have been determined, have been tentatively identified by the observation of predicted transitions of either isotopically substituted species or of related transitions, or by means of characteristic hyperfine structure. For example, the interstellar spectra of reactive free radicals such as CN, C_3N, C_2H, and C_4H and molecular ions such as HCO^+ and N_2H^+ were first assigned in this way. The interstellar rotational spectra of these species yield primary information about the molecular geometry and hyperfine parameters not previously available in terrestrial laboratories.

Even with the aid of additional transitions, isotopic substitution, and characteristic hyperfine structure, the task of assigning interstellar radio lines is formidable, increasingly so as detectors improve to reveal a forest of unidentified features. Currently unidentified spectral lines are probably more numerous than the list of detected interstellar species. The spectrum of the Orion molecular cloud, for example, illustrates the spectroscopic problem caused by crowding of adjacent lines, a problem which will only grow more severe as the resolution limit of overlapping features is approached in the next decade.

Once a new interstellar spectral line has been correctly identified by one of these methods, what more can be learned from a detailed analysis of the strength and shape of this line? The goal of such an analysis for the astrochemist is often the abundance of the emitting (or absorbing) species relative to the density of hydrogen in the cloud in which it has been observed. Typical values range from 10^{-5} for carbon monoxide to 10^{-10} for complex polyatomic molecules. In principle, at least, studies of molecular excitation and radiative transfer can also yield interesting astrophysical information about the kinetic temperature, magnetic fields, fractional ionization, and motions (collapse, rotation, turbulence) within a cloud.

The dominant process for producing an observable emission line at millimeter wave lengths is that of collision with molecular hydrogen. These inelastic but nonreactive collisions occur with large probability, sending molecules into excited rotational states. The temperature describing the relative populations of rotational levels is driven toward the gas kinetic temperature as hydrogen density, and hence frequency of collisions, increases. Because the gas is only slightly ionized, collisions with electrons are not important. Acting in the opposite sense, higher rotational levels return to lower levels both by collisions and by spontaneous emission of microwave photons.

In the low-density limit, the rotational levels can come to radiative equilibrium with the cosmic microwave background. The temperature describing the relative populations of the two levels of the observed transition is called the excitation temperature. Derived excitation temperatures for interstellar molecules generally are intermediate between the big-bang radiative temperature (2.7° K) and the gas kinetic temperature (10° to 30° K), reflecting the close competition between collisional and radiative effects for control of the rotational population. The collisional densities required to collisionally excite observable radio wave-length emission lines can be as low as 1000 per cc, for carbon monoxide, or as high as 1 billion per cc for water. Most interstellar molecules are subthermally excited, that is, the excitation temperature is less than the gas kinetic temperature.

The real-life complications of multiple scattering of the emitted photon on its way out of the molecular cloud, temperature and density gradients within the cloud, and the internal velocity field within the cloud are beyond the scope of this article, but are important aspects of current line-shape analyses. Let's consider a simplified example in which the measured excess of radiation, or brightness temperature (ΔT_B), received at the radio telescope from an idealized molecular cloud may be written as

$$\Delta T_B = (T_{ex} - T_R)(1 - \exp(-\tau))$$

where T_{ex} is the excitation temperature of the transition, T_R the background radiation temperature (usually 2.7° K), and τ is the optical depth of the transition, a quantity related to the molecular abundance.

The crux of the problem in interpreting interstellar spectral lines is to separate the effects of abundance and excitation. For lines of very low optical depth ($\tau \ll 1$), the observed intensity, ΔT_B, may be directly related to the molecular abundance. In the limit of high optical depth ($\tau > 1$), ΔT_B is simply proportional to the excitation temperature, which itself closely approaches the cloud kinetic temperature. For example, the $J = 1 \rightarrow 0$ transition of interstellar carbon monoxide is usually quite thick ($\tau \geqslant 10$), with measured excess brightness temperatures ΔT_B equal to the kinetic temperatures of 10° to 30° K found in dark clouds.

Since most interstellar molecules are observed not to be in thermodynamic equilibrium, even a good knowledge of the molecular abundance of the emitting species in the observed transition does not lead directly to the total molecular abundance summed over all energy levels, nor, introducing the cloud

About 50 interstellar molecules now have been detected

Known interstellar molecules[a]

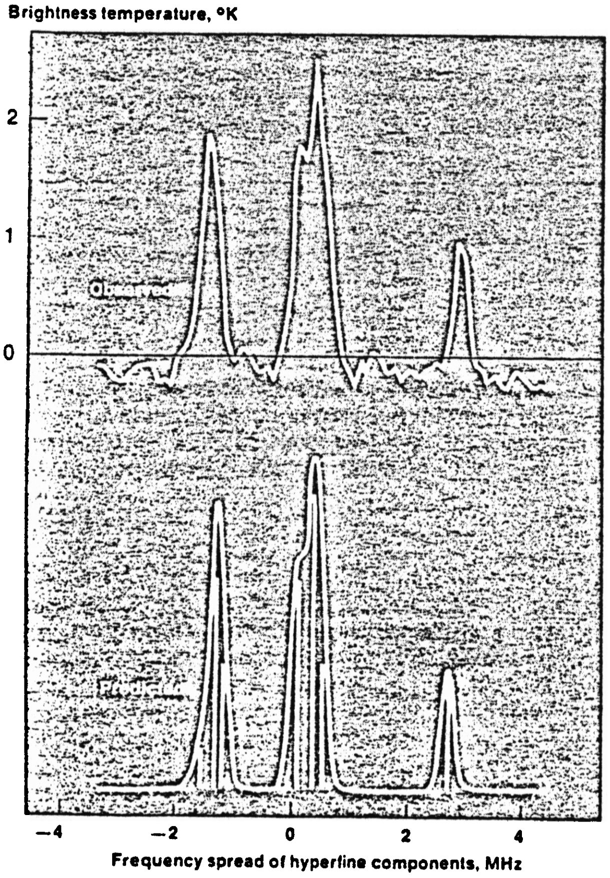
Name	Formula	Transition wave length	Isotopes
Hydrogen	H_2	Ultraviolet, infrared	D
Hydroxyl radical	OH	Radio, ultraviolet	^{18}O
Silicon monoxide	SiO	Radio	^{29}Si, ^{30}Si
Sulfur monoxide	SO	Radio	
Silicon monosulfide	SiS	Radio	
Nitrogen sulfide	NS	Radio	
Methylidyne ion	CH^+	Visible	^{13}C
Methylidyne	CH	Visible, radio	
Cyanogen radical	CN	Radio, ultraviolet	
Carbon monoxide	CO	Radio, ultraviolet	^{13}C, ^{18}O, ^{17}O
Carbon monosulfide	CS	Radio	^{13}C, ^{33}S, ^{34}S
...	CC	Infrared	
Nitric oxide	NO	Radio	
Water	H_2O	Radio	D, ^{18}O
Hydrogen sulfide	H_2S	Radio	
Sulfur dioxide	SO_2	Radio	
Hydrogen cyanide	HCN	Radio	D, ^{13}C, ^{15}N
Hydrogen isocyanide	HNC	Radio	D, ^{13}C
Carbonyl sulfide	OCS	Radio	
Formyl ion	HCO^+	Radio	D, ^{13}C
Formyl radical	HCO	Radio	
Ethynyl radical	CCH	Radio	
...	NNH^+	Radio	D
Nitroxyl radical (?)	HNO	Radio	
Ammonia	NH_3	Radio	D
Formaldehyde	H_2CO	Radio	^{13}C, ^{18}O
Isocyanic acid	HNCO	Radio	
Thioformaldehyde	H_2CS	Radio	
Cyanoethynyl radical	CCCN	Radio	
Acetylene	HCCH	Infrared	
Cyanoacetylene	HC_3N	Radio	^{13}C
Methane (?)	CH_4	Radio	
Formic acid	HCOOH	Radio	
Methanimine	CH_2NH	Radio	
Ketene	H_2CCO	Radio	
Cyanamide	NH_2CN	Radio	
Butadiynyl radical	CCCCH	Radio	
Methanol	CH_3OH	Radio	
Methyl cyanide	CH_3CN	Radio	
Formamide	NH_2CHO	Radio	
Methylacetylene	CH_3CCH	Radio	
Acetaldehyde	CH_3CHO	Radio	
Methylamine	NH_2CH_3	Radio	
Vinyl cyanide	CH_2CHCN	Radio	
Cyanodiacetylene	HC_5N	Radio	
Methyl formate	$HCOOCH_3$	Radio	
Dimethyl ether	CH_3OCH_3	Radio	
Ethanol	CH_3CH_2OH	Radio	
Ethyl cyanide	CH_3CH_2CN	Radio	
Cyanotriacetylene	HC_7N	Radio	
Cyanotetra-acetylene	HC_9N	Radio	

[a] As of June 1978. Note: Transition wave lengths are: ultraviolet, less than 4000 A; visible, 4000 to 7000 A; infrared, 7000 A to 1 mm; radio, 1 mm and greater.

geometry, to the ultimate goal of molecular density. Total molecular abundance is properly estimated by solving the statistical equilibrium problem for the lowest 10 to 20 energy levels with some detailed knowledge of collisional cross sections, kinetic and radiative temperatures, and hydrogen density. In the absence of this full treatment, bounds to total molecular abundance are crudely set by assuming that the molecular population is only in the two transition levels (lower bound), or that higher (unobserved) levels are populated by a Boltzmann distribution at the kinetic temperature (an upper bound, since higher levels are generally subthermally populated). Typical derived molecular abundances, relative to hydrogen, are in the range of 10^{-5} to 10^{-10}.

Optically thin lines measured with good signal-to-noise ratios yield excellent determinations of cloud velocity, with uncertainties of 0.1 km per second or less for lines of 2 to 20 km per second in width. Optically thick transitions, which can be thermalized at low collisional densities, make the best interstellar thermometers. Examples of such transitions are the atomic hydrogen and carbon monoxide lines. Kinetic temperatures of clouds determined from such transitions are probably accurate to 20 or 30%. Much less accurately determined are the molecular and hydrogen densities. Their derivation requires a long chain of reasoning, with weak links of uncertain excitation, chemistry, and cloud geometry. These derived densities are no more certain than a factor of three, and may be wrong by an order of magnitude.

Exotic species identified by matching observed spectrum with theoretical one



Note: Center frequency of the transition is 93173.39 MHz.

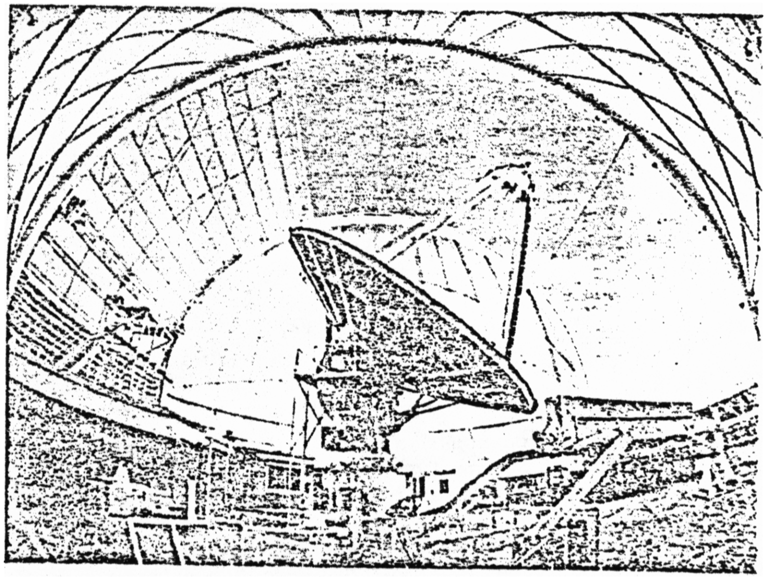
The observed and predicted $J = 1 \rightarrow 0$ rotational spectrum of the interstellar molecular ion N_2H^+. The top curve is the 3-mm emission spectrum observed by Barry Turner and Patrick Thaddeus in the Orion molecular cloud. The lower spectrum is one derived from molecular constants calculated theoretically, with no empirical data.

If the populations of the levels connected by the observed transition are inverted, unusually intense stimulated emission may be observed. The strongest such natural masers observed to date are the OH radical, water, and silicon monoxide, although several other polyatomic interstellar species are thought to show weak maser emission at low radio frequencies. The molecular abundance for strong masers cannot be obtained in the manner outlined above. The pointlike and time-variable emissions from the OH radical, water, and silcon monoxide mark the birthplace of new stars and the expanding circumstellar envelope of evolved stars.

Organics predominate

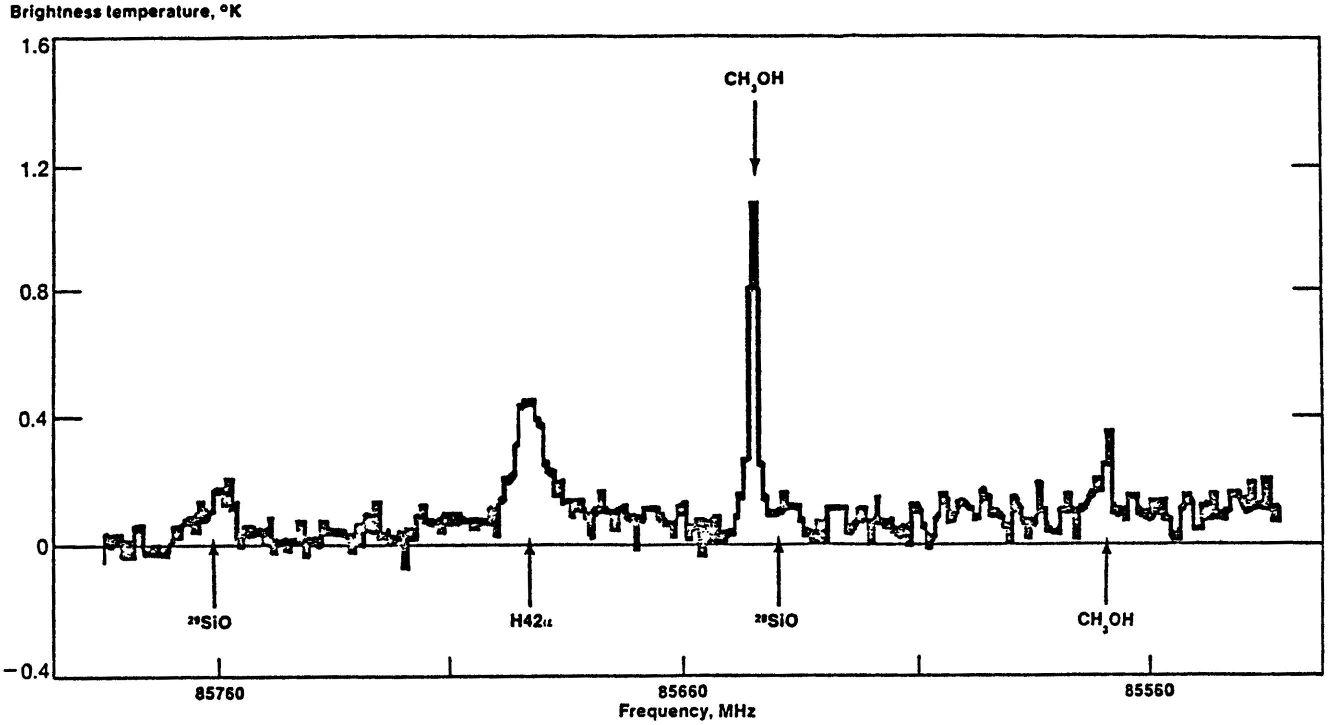
Any useful model of the interstellar chemistry must explain the abundance, relative to hydrogen, of the molecules detected in interstellar space. The interstellar chemistry observed so far is overwhelmingly organic; three quarters of the 50 known interstellar molecules contain carbon. Carbon monoxide dominates, binding perhaps 10% of the available cosmic carbon. Sulfur-containing species are common. Interstellar species containing a nitrogen-oxygen bond are apparently quite uncommon, being represented only by the very recently detected species NO and possibly HNO, despite numerous unsuccessful searches for NO^+, NNO, H_2NOH, and HNO_3.

Many interstellar species are stable, familiar terrestrial molecules. For a time early in the 1970's, astronomers thought that interstellar conditions always yielded off-the-shelf molecules, a crude working hypothesis that Patrick Thaddeus of the Institute for Space Studies of the Nation Aeronautical & Space Administration (NASA) has called the "Fisher Scientific" principle. However, with the detection of such exotic, nonterrestrial species as HCO^+, HNN^+, CCH, and HNC, this principle has been recognized as stemming from a bias toward selecting known, stable molecules with previously measured rotational transitions. Fully one third of the molecules now detected in interstellar space qualify as unfamiliar or unknown laboratory species, being either free radicals, molecular ions, or of a refractory nature.



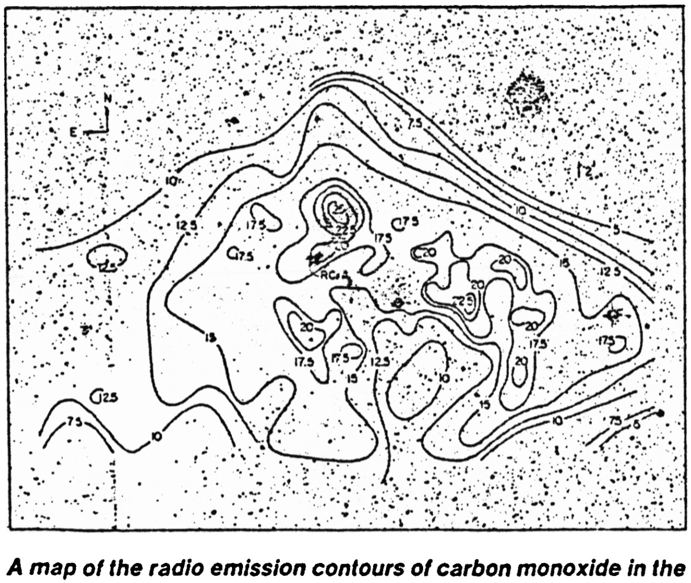
Nearly half of all new species that have been discovered in interstellar space were first observed on this 11-m-diameter radio-telescope of the National Radio Astronomy Observatory on Kitt Peak, near Tucson, Ariz., which operates in the 1-cm to 1-mm wave-length band

Improved detectors can reveal a crowd of spectral lines in interstellar space



An unusually crowded part of the 3-mm wave-length spectrum of the Orion molecular cloud, as observed at the National Radio Astronomy Observatory by Frank Lovas, Donald Johnson, David Buhl, and Lewis Snyder. Identified features include lines from two different symmetry species of methanol, two isotopic forms of silicon monoxide, and a Rydberg transition of atomic hydrogen.

Emission contours map the chemistry and dynamics of galactic clouds



A map of the radio emission contours of carbon monoxide in the dark cloud R Corona Australis, made at the Millimeter Wave Observatory at the University of Texas by Robert Loren. Maps of emission intensity contours of carbon monoxide and other molecules have helped evaluate chemical and dynamical cloud models. The closed contours define regions of equal radio intensity or brightness temperature in ° K. Carbon monoxide has proved especially useful for studying the collapse of interstellar clouds.

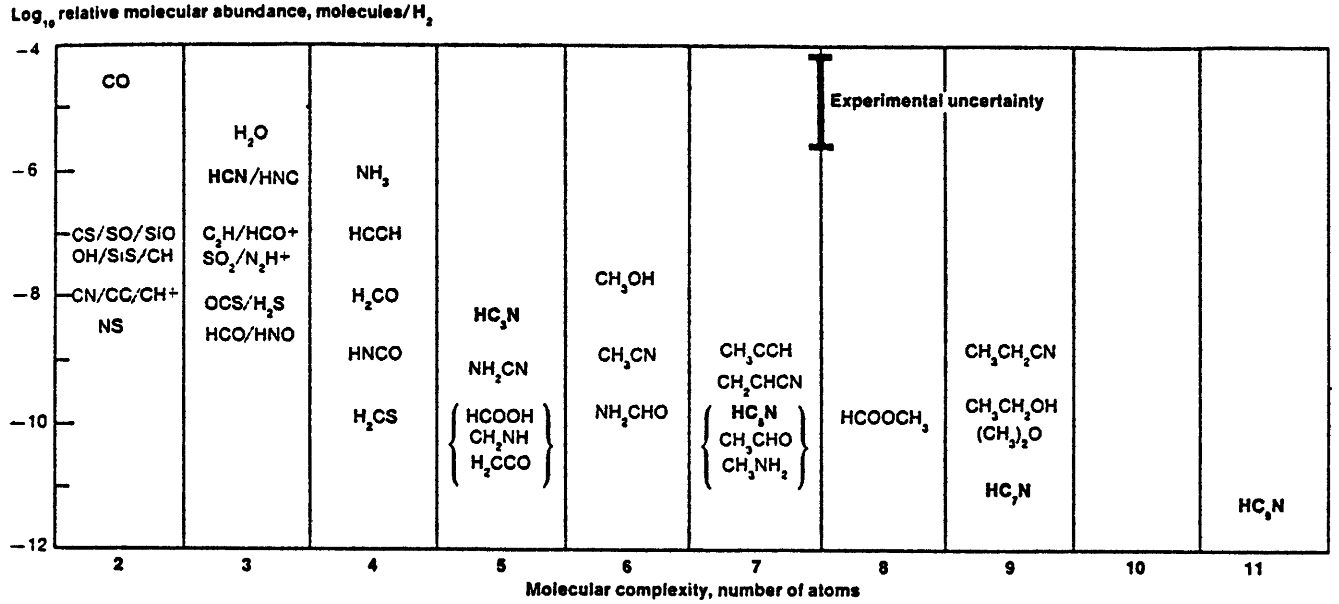
Unsaturated (hydrogen-poor) molecules appear to be more abundant than their saturated analogs, although this conclusion has been weakened in the past few years. Several saturated molecules have now been detected in high abundance. And it now is realized that the larger rotational partition function of saturated molecules compared to unsaturated species leads to an observational bias, at current detection limits, toward the unsaturated forms. For example, related interstellar molecules may be grouped in order of increasing hydrogenation:

CO	HCN	HCCCN	(hydrogen-poor)
H_2CO	CH_2NH	H_2CCHCN	↓
CH_3OH	CH_3NH_2	CH_3CH_2CN	(hydrogen-rich)

In each case, the unsaturated (hydrogen-poor) molecules probably are most abundant, the fully saturated (hydrogen-rich) molecules less abundant, but the partially saturated molecules least abundant. Carbon-carbon double bonds are quite rare, whereas fully unsaturated carbon-carbon triple bonds are common. This is puzzling in light of the enormous overabundance of hydrogen with respect to all other interstellar species. As determinations of abundance improve, the distribution of observed species and their degree of saturation may allow determination of the contributions of interstellar synthesis on grain surfaces relative to that in the gas phase. Grain-surface models predict a preponderance of hydrogen-rich molecules, gas-phase models predict that unsaturated species should be dominant.

One final observational constraint on theoretical models of interstellar chemistry is the apparent absence of interstellar ring molecules. Sensitive but unsuccessful radio searches have been made for five- and six-membered heterocyclic rings like pyridine and pyrimidine. Benzene, being nonpolar, lacks a radio rotational spectrum. The complexity of such rings (for example, 11 atoms for pyridine) is no longer a tenable argument against

Simpler molecules are more abundant in interstellar space



Abundances of interstellar molecules relative to molecular hydrogen. The observed abundance falls with increasing molecular complexity, but only gradually, especially with the sequence of cyanopolyacetylenes ($HC_{2n-1}N$). This suggests that more complex species may be discovered in abundances only slightly less than those now known.

their interstellar existence since the detection of the cyanopolyacetylenes with from one to nine carbon atoms in surprisingly high abundance. In fact, interstellar species of even greater complexity (more than 11 atoms) probably will be detected in only slightly lower abundance than currently known species.

Current theoretical models of interstellar chemistry are of two basic kinds: those employing gas-phase, two-body reactions and those invoking surface chemistry occurring on the cosmic dust grains. In either case, the interstellar molecules are now considered to be actually produced in the dark clouds where they are observed, rather than having been transported to these clouds from distant stellar or protostellar regions where higher temperatures and densities allow a richer chemistry to evolve. The typical conditions in dense interstellar clouds, where the density of hydrogen ranges from 100 to 1 million molecules per cc, preclude three-body, gas-phase collisions, and limit the kinetics to those exothermic reactions that have large cross sections and no activation energy at the interstellar temperatures of 10° to 50° K. Important reactions of this type include ion-molecule reactions and some radical recombinations.

Attempts to explain quantitatively the observed abundances of the optically detected diatomic species in diffuse clouds by a mechanism of radiative association in the gas phase ($C + H \rightarrow CH + h\nu$) began in the early 1950's. More recent work by several groups suggests a faster rate for this very inefficient process, but one that is still probably inadequate to explain the observed abundance of the molecules. For example, the model developed by William Klemperer of Harvard University and Philip Solomon (now at the State University of New York, Stony Brook) involves radiative association of CH and CH^+, followed by chemical exchange with C, N, or O to form C_2, CN, or CO. Abundances predicted by this model were in fair accord with the observed values for diffuse clouds. A more recent model, developed by Moshe Elitzur and William Watson of the University of Illinois, suggests that observed CH^+ abundances are best explained as the result of enhanced formation rates in the dense, warm gas behind interstellar shock waves.

As molecular radio astronomers began to discover more complicated polyatomic species in the darker and denser interstellar clouds, chemical models more appropriate to these conditions began to be developed in the early 1970's. One of the most successful of these models is that developed by Eric Herbst of William and Mary College and Harvard's William Klemperer. It involves rapid ion-molecule reactions in cold, weakly ionized molecular hydrogen clouds. The scheme is driven by cosmic-ray ionization of hydrogen ($H_2 \xrightarrow{CR} H_2^+ + e$), followed by rapid formation of the stable hydrogen ion H_3^+ by the sequence:

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

$$H_3^+ + H_2 \not\rightarrow \text{(endothermic)}$$

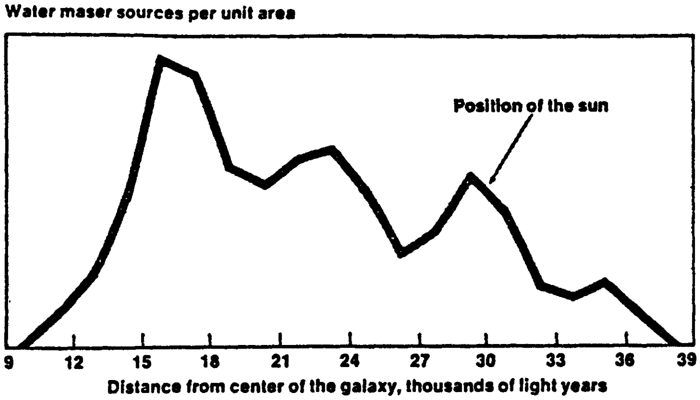
This protonated molecular hydrogen is then the starting point for the formation of larger molecules via reactions like

$$H_3^+ + \begin{Bmatrix} CO \\ N_2 \end{Bmatrix} \rightarrow \begin{Bmatrix} HCO^+ \\ HNN^+ \end{Bmatrix} + H_2$$

Ion-molecule schemes of this type have been reasonably successful in explaining the observed interstellar chemistry for species of moderate complexity (those containing four atoms or less). The detection, identification, and derived abundances of the molecular ions HCO^+ and HN_2^+ have strongly supported such ion-molecule models, which ignore completely the contribution of surface chemistry on dust.

Despite great uncertainties in the nature of the interstellar grains, chemical models involving surface chemistry also have been developed in some detail. The most abundant interstellar molecule, hydrogen, is formed overwhelmingly on dust grains. Models involving dust grains circumvent the problem of low bimolecular reaction rates, since the grain acts as the third body.

Grain chemistry models are of two types—those in which the grains play a passive role, and those in which the grains are catalysts, lowering activation energies and promoting rapid reactions. The four important processes in all grain models are adsorption of an atom from the gas, its migration over the grain surface via quantum mechanical tunneling, its reaction with a second adsorbed atom (or molecule), and ejection or evaporation of the molecule formed by the reaction back to the gas phase where it can be observed. Obviously, the details of these



Peak in water maser emissions pinpoints region of active star formation

Radial distribution in the galaxy of regions of active star formation, as indicated by intense water maser emission at a wave length of 1.3 cm. The plot represents the number of water masers found in each annular ring of the galactic plane, normalized to the area of that region to give a surface number density of water sources as a function of increasing radial distance from the center of the galaxy. The sharp peak at about 1700 light years from the center suggests that this is a ring of star birth; similar evidence shows up in the distribution of carbon monoxide, x-rays, γ-rays, and pulsars.

four processes depend critically on the temperatures, composition, and surface properties of the grain.

A pioneering grain chemistry model was proposed in 1972 by Edwin Salpeter of Cornell University and William Watson of the University of Illinois. More recently, Mark Allen and G. Wilse Robinson at California Institute of Technology have developed an extensive model involving 600 reactions in a time-dependent calculation of the molecular abundances of 372 different species! Their model basically relies on free radical recombinations on inert grain surfaces to achieve peak molecular abundances in 100,000 to 1 million years, time scales similar to those predicted in time-dependent, gas-phase models employing ion-molecule reactions. More recent models strive to include the combined effects of both gas-phase and surface reactions. Only when the physical and chemical nature of individual clouds has been determined with greater reliability will the question of the relative importance of gas-phase vs. grain-surface chemistry in dense clouds be resolved.

Interstellar molecules also may be formed by the breakup of the interstellar grains or at sites of enhanced chemistry in the warm, dense postshock regions in cloud-cloud collisions. The possibility that grains may actively catalyze the formation of interstellar molecules has been suggested by Lester Anders of the University of Chicago, although the necessary conditions—temperatures greater than 300° K and hydrogen molecules in abundances of 10^{15} per cc or more—may be available only in the protostellar cores of black clouds. At the very least, the grains are essential in the formation of molecular hydrogen, the protection of interstellar molecules from ultraviolet photodissociation by starlight, and the removal of most of the heavy elements from the interstellar gas.

Recent developments

Interstellar molecular spectroscopy has promised a deeper insight into the places and processes of star birth, long hidden from optical astronomers by dark dust clouds. Detailed analyses of line shapes in sophisticated models of radiative transfer allow, in principle, the density of hydrogen, temperature, and velocity to be mapped as a function of position in the cloud. The spatial resolution is limited by the angular extent of the telescope beam, a few arc minutes corresponding to linear distances of several light years for typical galactic distances. Much higher spatial resolution, less than 10^{-3} second of arc, has been achieved in interferometric studies of the intense pointlike maser emissions of water and OH radicals, using two or more radiotelescopes separated by continental distances. The extension of interferometric techniques to millimeter wave lengths, as is now being actively pursued by several different groups in the U.S. and Western Europe, should eventually reveal a detailed picture of the protostellar cores of collapsing molecular clouds.

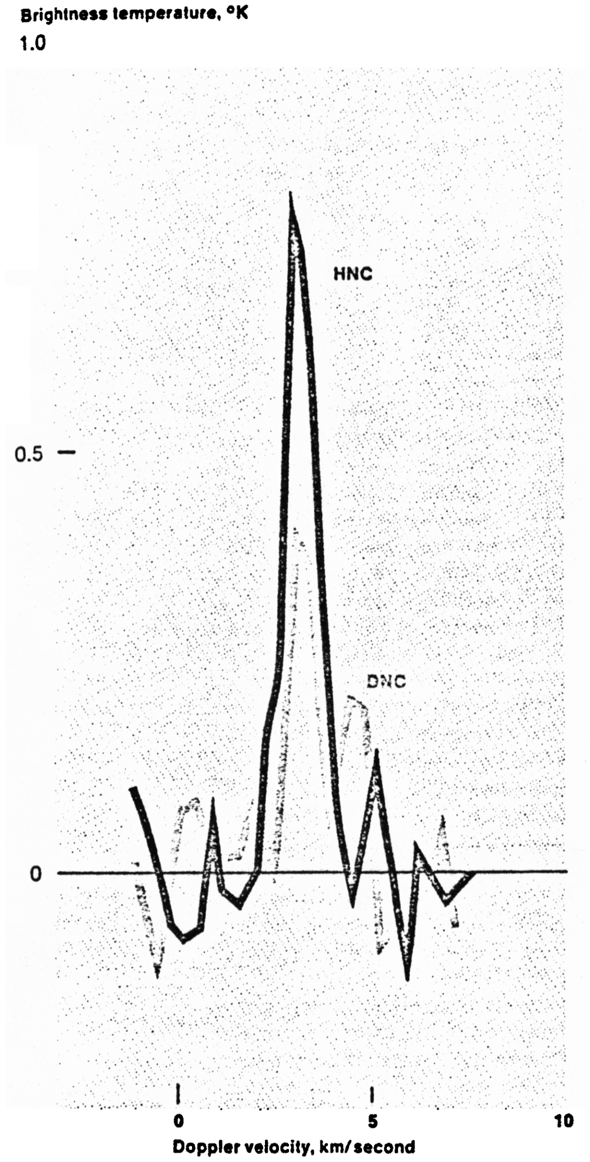
Single-dish mapping of the radio emission intensity contours of several different molecules in a particular dark cloud has been useful in recent years for evaluating chemical and dynamical models of such clouds. Robert Loren of the University of Texas, for example, has made detailed comparisons of the radio emission spectra of CS, HCO^+, H_2CO, and $C^{18}O$ from R Corona Australis, a particular dark cloud in the Southern Cross constellation. Carbon monoxide, the most abundant interstellar molecule after hydrogen, can be collisionally excited at quite modest interstellar gas densities (300 molecules of hydrogen or more per cc). Consequently, a map of ^{12}CO intensity in the same cloud reveals radio emission that is more intense and spatially extended than that of less abundant species, which require more specialized conditions of excitation. Carbon monoxide in its several isotopic forms has proved especially valuable as a tool for studying the initial phase of the collapse of interstellar clouds to form new stars. A detailed study of the observed line shapes and Doppler velocities of interstellar ^{12}CO and ^{13}CO in several dark clouds by Loren and his colleague Ronald Snell has provided the first direct experimental evidence for collapse in such clouds. The line from ^{13}CO originates from deeper within the cloud than that from ^{12}CO. Since the ^{13}CO appears to be moving away from earth more rapidly than is the ^{12}CO, the gas within the cloud is presumed to be collapsing more rapidly than that on the surface.

Molecular radio astronomy is being applied to the death of stars, as well as to their birth. In particular, Benjamin Zuckerman of the University of Maryland and coworkers have been studying the molecular lines emitted by cool, luminous objects thought to represent the poorly understood transition phase between evolved red-giant stars and the later stage called "planetary nebulae." The observed molecular composition depends strongly on the stellar abundance of oxygen relative to carbon. Oxygen-rich, cool stars characteristically show microwave emission lines of OH radicals, water, and silicon monoxide; carbon-rich stars are more likely to show carbon monoxide emission in expanding circumstellar shells.

The similarity of time scales for chemical and gravitational changes (100,000 to 1 millions years) in collapsing dark clouds has led to recent models linking the evolution of these changes. The initial phase of the gravitational contraction of the cloud occurs isothermally as the collapse energy is efficiently radiated out of the cloud by rotational emission lines of CO, HD, and other species. Interstellar chemistry and star formation enjoy a symbiotic relationship!

Star formation is not an isolated process. Stars are born in groups (clusters), and even in groups of groups (associations). Waves of star-birth seem to sweep through dark clouds, driven by the energy released by earlier generations of stars. On an even grander scale, radio astronomers are tracing out the pattern of dense clouds throughout the Milky Way and finding galactic waves of star formation apparently associated with the galaxy's overall spiral pattern. As in mapping dark clouds, the molecule preferred for galactic structure studies is carbon monoxide, which now is used to probe the unusual motions in the galactic core as well as the thickness and warp of the galactic

Deuterated molecules' spectra may be nearly as strong as from normal species



Interstellar rotational spectra of HNC and DNC observed in the dark cloud Lynds-134, as reported by Ronald Snell and Alyn Wooten of the University of Texas. The similar intensities of these two spectra imply similar abundances of HNC and DNC. Since the cosmic atomic ratio of deuterium to hydrogen is about 10^{-5}, deuterium must be enriched in the observed DNC molecule by a factor of about 10^5 over the cosmic atomic ratio.

plane itself. Individual clouds revealed in the millimeter wave length radiation of carbon monoxide have masses of an order of 100,000 times the mass of the sun. Thousands of such clouds exist around the galaxy.

The radial distribution of these clouds defines a giant galactic ring with the peak molecular density occurring at about half the distance between the center of our galaxy and earth, which contains perhaps 90% of all interstellar matter. This same radial distribution occurs for other indicators of star formation, such as galactic x-rays, supernova remnants, and regions of ionized gas around massive stars. This molecular ring is in sharp contrast to the much flatter radial distribution of atomic hydrogen, as determined from radio emission at a wave length of 21 cm. From the position of the earth inward toward the galactic center, interstellar hydrogen is largely molecular; from the earth outward, hydrogen is predominantly atomic. The new picture of the galactic plane, as defined by carbon monoxide emission, has been primarily the work of Butler Burton and Mark Gordon of the National Radio Astronomy Observatory and of Philip Solomon and his coworkers.

Another tracer of galactic star formation is the radio emission from interstellar water masers. The physical conditions necessary to produce such intense water signals are in regions of the Milky Way where star formation is active.

Interstellar molecules also have been applied to study of the chemical history of the galaxy. As described above, pregalactic matter was essentially pure hydrogen and helium but subsequent processing of the interstellar matter through stellar interiors has continually enriched interstellar space with heavier elements. The large shifts in transition frequency for isotopically substituted moments of inertia make the rotational transitions of such interstellar molecules as H_2CO, CO, HCO^+, HCN, CS, and SiO ideal for determining the abundances of the less common isotopes (D, ^{13}C, ^{17}O, ^{18}O, ^{15}N, ^{30}Si, ^{33}S, ^{34}S).

The first galactic surveys of the relative abundances of isotopes in interstellar molecules unexpectedly indicated that they are found in about the same ratios in space as on the earth, within a factor of three. More recent observations (especially by groups at Bell Labs, Caltech, and the University of Massachusetts) have led to the conclusion that the ratios of both ^{13}C to ^{12}C and of ^{17}O to ^{18}O in the galaxy have increased since the solar system formed 4.5 billion years ago. Isotopic ratios also vary from cloud to cloud, though no obvious variation with galactocentric distance is apparent. And the galactic center has anomalous isotopic ratios, suggesting a unique nuclear history.

Several pitfalls exist in deducing elemental isotopic ratios from ratios of related molecules. Line saturation of the common species distorts the apparent relative abundance. Two related lines may experience different interstellar excitation. And chemical fractionation, a natural isotopic enrichment process, can distort the molecular isotopic ratio from the true elemental isotopic value.

Isotopic fractionation in carbon monoxide, for example, may occur via

$$^{13}C^+ + {}^{12}CO \rightarrow {}^{12}C^+ + {}^{13}CO$$

where the exothermicity of the forward reaction ($\Delta E/k \sim 35°$ K) results from the difference in the zero-point vibrational energies of ^{13}CO vs. ^{12}CO. This means simply that ^{13}CO is more stable than ^{12}CO by an amount of energy equivalent to a temperature of 35° K. Thermodynamic equilibrium at interstellar cloud temperature could easily shift $^{13}C/^{12}CO$ by a factor of three or more from the true elemental $^{13}C/^{12}C$ ratio.

A much more dramatic chemical fractionation is inescapable in the case of deuterated interstellar molecules, for which the energy change upon deuteration ($\Delta E/k \sim 500°$ K) far exceeds the thermal energy available in clouds. The ratio of deuterium to hydrogen in nearby interstellar space, as measured using the Copernicus satellite, is 10^{-5}. Measurements from the same satellite of the deuteration in molecular hydrogen indicate that the ratio HD/H_2 in diffuse clouds is 10^{-6}. Radio astronomers are finding that signals from deuterated molecules in dark clouds are about as strong as those from normal species, implying fractionation effects of nearly 10^5. The interstellar molecules already detected in deuterated form include HD, DCN, HDO, DCO^+, NND^+, NH_2D, DNC, and possibly CH_3NHD. Of these species, those observed in typical galactic molecular clouds show deuterium enhancements of about 10^3, while the same species observed in the cooler dark clouds often show enhancements of 10^4 or higher.

The original interest in deuterated molecules was cosmological. A ratio of deuterium to hydrogen of about 10^{-5} is considered by cosmologists to require primordial conditions which lead to an open universe. Indeed, the observation of a DCN/

$H^{13}CN$ ratio in the galactic center at only a tenth the galactic average has been used to argue for a solely cosmological origin of deuterium. However, the observation of enormous chemical fractionation in deuterated interstellar molecules has shifted the focus from cosmology to chemistry and may lead to a better understanding of specific chemical pathways in interstellar clouds. One important recent conclusion has been that the fractional ionization in dark clouds is very low. Such essentially neutral clouds are probably unable to retain their magnetic fields, and hence may collapse more rapidly.

An important advance in understanding the theoretical kinetics of interstellar species has been the recognition that the formation of interstellar molecules by means of radiative association, which is very inefficient for diatomic species like CH^+, becomes enormously more favorable for polyatomic species with numerous internal vibrational modes. Considerable effort has been devoted to the details of the key reaction

$$C^+ + H_2 \rightarrow CH_2^+ + \text{photon}$$

as the starting point for the hydrocarbon chemistry in dark clouds. Radiative association also has been proposed for the formation of larger, polyatomic molecules, those containing six or more atoms, formed by ion-molecule reactions as well as by neutral free-radical recombinations. Recent laboratory measurements give some support to the large theoretical rates of these radiative association reactions for polyatomic species in interstellar clouds. These results suggest that large interstellar molecules may form easily in dense clouds without the assistance of grain-surface reactions. The resulting molecule rapidly partitions the energy of reaction among its many vibrational modes until a stabilizing vibrational photon is emitted. In a sense, the large polyatomic molecule may be considered to act as its own third body.

Clearly, progress in both the spectroscopic and kinetic studies of interstellar molecules depends heavily on improved laboratory measurements of transition frequencies, photolifetimes, thermodynamic stabilities, and kinetic rates.

The explosion of information abour interstellar molecules that has taken place in the past decade has followed at each stage the development of low-noise coherent detectors sensitive to progressively shorter wave lengths. Attenuation by pressure-broadened transitions of atmospheric gases is a significant problem, especially near frequencies of 22 GHz (H_2O), 59 GHz (O_2), 118 (GHz (O_2), 183 GHz (H_2O) and above. The 183 GHz transition of interstellar water has been recently detected in the Orion molecular cloud by a group of NASA astronomers taking their telescope and spectrometer above most of the earth's water vapor in the G. P. Kuiper Airborne Observatory, a NASA jet. This result is particularly significant, since the observed water emission appears to be extended and normally excited. Unlike the pointlike, anomalous masering signals from the lower frequency waterline at a wave length of 1.3 cm, for which no reliable abundances can be derived, the more nearly thermal water emission at 183 GHz indicates an abundance of water in the cloud, relative to hydrogen, of 10^{-6}. Water may even rival carbon monoxide in abundance, making interstellar clouds much wetter than previously thought. (This would, incidentally, lower the estimated proof of 0.2 of the ethanol cloud in the galactic center!) Even wetter interstellar conditions have been recently derived from the ground-based observation of $H_2{}^{18}O$ by a collaboration of astronomers from Caltech, the University of Massachusetts, and Bell Labs.

The distinction between radio and infrared astronomy is rapidly fading as radio astronomers push to submillimeter wave lengths to meet infrared astronomers working in the far infrared. Already, improvements in sensitivity and spectral resolution in the near-infrared have led to the detection of vibrationally excited hydrogen molecules in shock fronts in the Orion cloud by astronomers at the University of Arizona, as well as the detection of vibration-rotation lines of circumstellar acetylene and hydrogen cyanide in cool, evolved stars by Donald Hall and coworkers at the Kitt Peak observatory. High-resolution spectroscopy of interstellar and protostellar regions at far-infrared and millimeter wave lengths will most certainly be one of the most fruitful research areas of astrochemistry in the next decade, particularly if new instrumentation, such as the proposed National Radio Astronomy Observatory's 25-m-diameter telescope on Mauna Kea in Hawaii, is built.

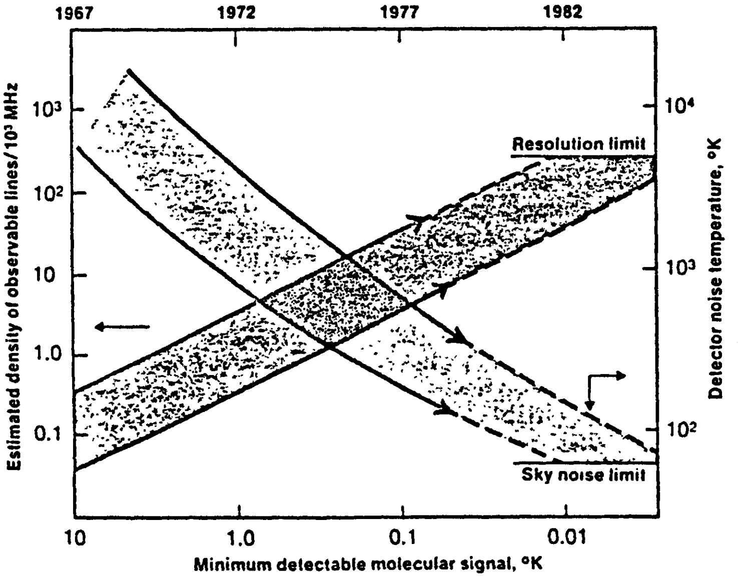
What about chemistry beyond the Milky Way? Just as optical astronomers in recent years, in analyzing the starlight from other galaxies, have found that the abundances of elements there are similar to those in our own galaxy, molecular radio astronomers have found even more recently that extragalactic chemistry produces several familiar interstellar molecules with typical relative abundances. The recently reported detection of carbon monoxide and hydrogen cyanide in several nearby galaxies brings the total number of known extragalactic species to six—OH, H_2O, H_2CO, CO, HCN, and H_2.

Isotopically substituted extragalactic molecules such as ^{13}CO have yet to be detected conclusively beyond our galaxy, but anticipated improvements in the sensitivity and angular resolution of detectors clearly suggest that detailed studies of the chemical evolution of other galaxies soon will be possible. The new discipline of extragalactic chemistry may eventually give us a broader perspective of the origin of life in our own galaxy and a better estimate of the chances for life beyond the Milky Way, as well as the probable chemical similarity of that life to our own.

The next 10 years

The next decade of interstellar chemistry promises as much excitement as the first. The coming generation of low-noise receivers will permit the detection of new interstellar species in the parts-per-trillion range. It is likely that the near future will bring the discovery of alkanes beginning with propane, cyanopolyynes containing more than 11 carbon atoms, and

Increasing detector sensitivity is making more spectral lines observable



With the continuing development of low-noise detectors for use in molecular radio astronomy, receiver temperatures have fallen from early values of more than 10,000° K toward the limiting sky brightness (less than 100° K) and the number of detectable molecular transitions per unit band width has increased rapidly toward the resolution limit of overlapping lines.

Isotopic ratios in the galaxy are generally similar to those in the solar system

		Observed ratio[a]		
Isotope(s)	Molecule(s)	Galaxy[b]	Galactic center	Solar system
$^{12}C/^{13}C$	CO, H_2CO, CS, HCN, CH^+	30–60	15–45	89
$^{17}O/^{18}O$	CO	0.2–0.3	0.31	0.19
$^{33}S/^{34}S$	CS	0.2	0.2	0.18
$(^{13}C/^{12}C)\cdot(^{32}S/^{34}S)$	$^{13}CS/C^{34}S$	0.4–0.6	0.6 ± 0.2	0.26
$(^{12}C/^{13}C)\cdot(^{15}N/^{14}N)$	$HC^{15}N/H^{13}CN$	0.23	0.02 ± 0.02	0.33
$(D/H)\cdot(^{12}C/^{13}C)$	$DCN/H^{13}CN$	0.1–0.2	0.018	0.013
$(^{12}C/^{13}C)\cdot(^{18}O/^{16}O)$	$C^{18}O/^{13}CO$	0.06–0.12	0.06	0.18
$^{28}Si/^{30}Si$	SiO	31 ± 8	---	30
$^{29}Si/^{30}Si$	SiO	1.2 ± 0.5	---	1.52

a Experimental uncertainties are typically 10 to 20% except as noted. Solar system values have no uncertainty. b Represents the range of values observed throughout the galaxy; silicon ratios are for the Orion A molecular cloud only.

molecules having aromatic rings. Radio searches for the simplest amino acid, glycine, are already under way.

An important development in instrumentation will be the extension of coherent detectors to submillimeter (far infrared) wave lengths, with future observations to be made from "dry" sites such as Mauna Kea, high-flying jets, or orbiting observatories. The improved spatial resolution of the proposed 25-m telescope on Mauna Kea will itself be surpassed by interferometric systems employing two or more radio dishes to probe the protostellar cores of collapsing clouds and the chemistry of distant galaxies.

With expected improvements in sensitivity and spectral resolution of far-infrared detectors, vibration-rotation bands in the 3- to 100-micrometer range will be detected for new interstellar species, especially such currently "unobservable" species as carbon dioxide, which lack pure rotational spectra in the millimeter band. The microwave detection of interstellar methane has been recently reported by Kenneth Fox and Donald Jennings of NASA's Greenbelt, Md., laboratory. The assigned transitions are intrinsically very weak, and result from a centrifugal distortion of the molecule from its nonpolar tetrahedral shape.

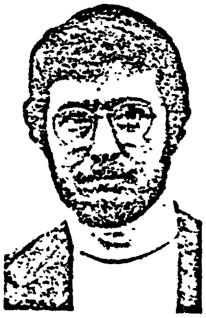
Far-infrared observations of circumstellar and interstellar dust grains certainly will clarify their composition and may explain the uncertain role of dust in interstellar chemical models. Newly observed but unidentified spectral features in the 1-to-20-micrometer band will be correctly assigned. The current controversy over the reality of an interstellar carbonate spectral feature near 11 micrometers will be resolved.

One of the outstanding spectroscopic puzzles of astrochemistry has been the origin of the "diffuse interstellar lines," an intriguing group of at least 30 broad optical interstellar absorption features, first observed more than 40 years ago and still unidentified. These have long been thought to result from an absorbing species in or on the cosmic dust grains. Recent studies, however, have revived the possibility of a gaseous molecular origin for these interstellar features, with suggestions ranging from hydrogen to porphyrins. A very promising possibility for producing these diffuse bands, recently suggested by A. E. Douglas of the Herzberg Institute of Astrophysics, Ottawa, Ont., are molecules related to the cyanopolyacetylenes.

A better understanding of the nature of interstellar chemistry both in and beyond the Milky Way will broaden our perspective on the chemical evolution of our own solar system, including its comets and the primitive earth, and of life itself. □

Selected readings

"CNO Isotopes in Astrophysics," Audouze, J., Schramm, D. (eds) Reidel, Dordrecht (1978).
"Atomic and Molecular Physics and the Interstellar Medium," Balian, R., Encrendz, P., Lequeux, J., (eds) Les Houches Summer School, 1974, Session XXVI, North Holland Publishing Co. (1975).
Dalgarno, A., Black, J. H., Molecule Formation in the Interstellar Gas, *Rep. Progr. Phys.*, **39**, 573 (1976).
Herbst, E., Klemperer, W. A., "The Formation of Interstellar Molecules," *Phys. Today*, **29**, 32 (1976).
Hoyle, F., "Astrochemistry, Organic Molecules, and the Origin of Life," *Mercury*, January–February 1978, p. 2.
Salpeter, E. E., "The Formation and Destruction of Dust Grains," *Ann. Rev. Astron. Astrophys.*, **15**, 267 (1977).
Somerville, W. B., "Interstellar Radio Spectrum Lines," *Rep. Progr. Phys.*, **40**, 483 (1977).
Townes, C., "Interstellar Molecules," *Observatory*, **97**, 52 (1977).
Turner, B. E., "Molecules in Space," *Sci, Amer.*, **228**, 51 (1973).
Watson, W. D., "Interstellar Molecule Reactions," *Rev. Mod. Phys.*, **48**, 513 (1976).
Zeilick, M., "The Birth of Massive Stars," *Sci. Amer.*, **238**, 111 (1978).
Zuckerman, B. "Interstellar Molecules," *Nature*, **268**, 491 (1977).
Zuckerman, B., Palmer, P., "Radio Radiation from Interstellar Molecules," *Ann. Rev. Astron. Astrophys.*, **12**, 279 (1974).



Dr. Richard H. Gammon, 35, is director of science at the Pacific Science Center, Seattle, Wash., and affiliate associate professor in the chemistry and astronomy departments at the University of Washington. Gammon completed his undergraduate work in chemistry at Princeton in 1965 and earned a Ph.D. in physical chemistry at Harvard in 1970. He became interested in molecular beam radiospectroscopy while completing his doctoral research with professor William Klemperer at the time when radio detection of polyatomic molecules in interstellar clouds was first reported. He did postdoctoral research in astrochemistry at the University of California, Berkeley, and continued research on interstellar molecules at the National Radio Astronomy Observatory in Charlottesville, Va. In 1974, learning that a group of Brazilian astronomers had just put into operation the first millimeter-wave radio telescope in the southern hemisphere, he went to São Paulo to search for water signals from the virtually unexplored southern Milky Way. Returning to the U.S. in 1976, he worked for Battelle Pacific Northwest Laboratories in Seattle, applying the techniques of molecular radio astronomy to the remote sensing of stratospheric trace gases, and later taught astrochemistry and astronomy at the University of Washington. Gammon joined the staff of Pacific Science Center this year.