

EXTRATERRESTRIAL MOLECULES: PRESENT AND FUTURE OBSERVATIONS FROM SPACE

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ABSTRACT

In the last ten years Molecular Astrophysics has become an extremely interesting field of interdisciplinary research as a result of unexpected discoveries of complex organic molecules made by radioastronomy in many regions and objects of the Galaxy. Since not all molecules have detectable transitions through the atmospheric windows, the development of UV and IR space astronomy will allow us to study new important molecular transitions in the interstellar medium and in the atmospheres of cool stars and comets. In this paper the present status of molecular astrophysics will be described and special emphasis will be devoted to the importance of IR space astronomy for the future knowledge of molecular species in the interstellar medium and in the atmospheres of Carbon stars where the low temperatures are particularly suitable for infrared studies

1. INTRODUCTION

The study of extraterrestrial molecules represents one of the most exciting fields of modern research in astrophysics which developed in the last ten years as a result of unexpected discoveries of complex organic molecules made by radioastronomy in many regions of the Milky Way and in other galaxies.

Such discoveries were possible because of the transparency

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of our atmosphere in the wavelength region above 1 mm and because of the high resolution achieved by modern radiotelescopes.

But not all molecules have detectable transitions in the microwave or radio region (e.g. H_2 and CH_4), therefore the development of UV and IR astronomy outside the absorbing layer of the atmosphere will permit the study of new important molecular transitions throughout the Universe.

The knowledge of molecular (and also atomic) species and their formation mechanisms in the interstellar medium can help to:

- 1.) Describe the matter exchange between interstellar gas and stars in which, especially in the supernova phase, nucleosynthesis starts.
- 2.) Determine the radiation losses in the gas cloud since the molecules can strongly radiate in the infrared.
- 3.) State the physical conditions in the cloud by using the molecules as indicators.
- 4.) Clarify the processes beginning with the formation of a protostar up to the birth of planets since molecules are the precursors of dust and condensed matter.
- 5.) Understand the physics of interstellar MASER and DASER processes which occur in dark interstellar clouds.
- 6.) Verify if aminoacids of the same extraterrestrial species of those contained in the Murchinson and Allende meteorites are present in the interstellar medium.
- 7.) Compare interstellar with cometary molecules in order to examine the origin and nature of Comets.

Extraterrestrial molecules could be classified in five categories: stellar, planetary, interstellar, cometary and meteoric.

A survey covering all molecules present in the Universe outside our atmosphere is not the purpose of this work where special emphasis will be devoted to those molecules relevant for a better understanding of matter exchange between the interstellar medium and stellar atmospheres and for a more detailed spectral classification of cool stars on the basis of new molecular species.

Since infrared astronomy is the most promising branch for future discoveries and studies of extraterrestrial molecules, especially from space facilities, the advantages of this technology will be particularly emphasized in this work.

2. MOLECULES IN THE INTERSTELLAR MEDIUM

The first interstellar molecules were discovered in 1937-

1938 (CH, CN, CH⁺) at 3700-4300 Å by means of high resolution spectroscopy in absorption spectra of diffuse interstellar clouds.

In the same period large diffuse bands in the range 4400-6100 Å, with a bandwidth of 10 Å, were discovered in the interstellar medium, but up to now identification of the bands has not been made. G. Herzberg suggests that these bands can be attributed to a predissociation of polyatomic molecules.

In 1968, radio astronomers at MIT could identify the first radio molecule, OH, at 18 cm wavelength. In the same year the discovery of the first polyatomic molecule, NH₃, at 1.26 cm in Sagittarius B 2 jolted the theories of interstellar matter chemistry because at the low temperature and density of interstellar clouds, the formation of polyatomic molecules was believed to be impossible.

In the following years the discovery of new molecules, especially organic and complex, increased sharply and brought also many challenging problems: the disproportionate ratio of organic to inorganic molecules, indications of non-terrestrial abundances of isotopes, molecular spectra non identified in laboratory, the presence of interstellar MASER and DASER (inverse MASER).

The 13 inorganic, the 35 organic molecules and the 5 molecular ions discovered in interstellar clouds till July 1978 are summarized in Table I. Among them the most important from the physical point of view are: OH and H₂O because of their MASER action, CO and H₂CO because they offer the possibility of studying the ¹²C/¹³C ratio through the entire galaxy leading to important conclusions about the isotope distribution. H₂CO is also a most peculiar interstellar molecule because of its anomalous line absorption at 6.21 cm in relatively dense clouds and dark where normally OH-MASER emission is observed. Since no background sources are present in these clouds, the H₂CO excitation temperature must be less than the 3°K cosmic background. This anomalous refrigeration must be originated by an inverse MASER mechanism (called also DASER) which is unknown in terrestrial laboratories where such physical conditions are not reproducible. The presence of formic acid (HCOOH), Methylamine (CH₃NH₂) and Dimethyl ether (CH₃)₂O in Orion suggests also that simple biomolecules like the aminoacids glycine, alanine etc. could be discovered; therefore the efforts of molecular radioastronomy are channeled today in this direction.

The possibility of using space facilities for molecular search has opened to the interstellar spectroscopy the two

TABLE I

INTERSTELLAR MOLECULES

A) <u>Inorganic Molecules</u>			Observed in absorption or emission		
	MOLECULE			D(eV)	I(eV)
OH **	Hydroxyl	2.2/5/6.3/18cm 1222/3078 A	A/E	4.40	13.10
H ₂ O**	Water	1.35cm	E	5.10	12.60
H ₂	Hydrogen	1000/1120 A-2.12	A	4.47	13.60
H ₂ S	Hydrogen	1.8mm	E	3.77	10.42
HD	Sulphide	1066/1054 A	A	4.51	
HDO	Monodeuterated Water	3.72mm	E		
HNO	Nitroxyl			2.11	
NH ₃	Ammonia	1.26	E		10.2
SiO	Silicon Monoxide	2.31-3.45mm	E	8.10	
SiS	Silicon Sulphide	2.75-3.3mm	E	6.37	
SO	Sulphur Monoxide	2.17-3.02mm	E	3.96	10.70
NS	Nitrogen Sulphide	2.60mm	E	6.0	
SO ₂	Sulphur Dioxide	3.46-3.58mm	E		12.34
B) <u>Organic Molecules</u>			A or E	D(eV)	I(eV)
CH**	Methylene	3886.4/3890.2/4300 A	A	3.47	10.6
CN**	Cyanogen	3874.6 A/2.64 mm	A/E	6.13	14.0
CO	Carbon Monoxide	1200/1600 A-870 1.3/2.6mm	E	11.09	14.0
CS	Carbon Monosulphide	2.04mm	E	7.60	10.6
HCN**	Hydrogen Cyanide	3.38-3.47mm	E	4.88	13.7
HNC	Hydrogen Isocyanide	3.3mm	E		
OCS	Carbonil Sulphyde	2.74mm	E		
C ₂ H	Ethynil Radical	3.43mm	E	5.72	11.3

B) Organic Molecules cont'd

MOLECULE			A or E	D(eV)	I(eV)
DCN	Deuterium Cyanide	13.8mm	E		
HCO	Formyl Radical	3.46mm	E	1.17	9.8
H ₂ CO	Formaldehyde	2.0/2.1mm-1.03/2.07 /6.21cm	E/A	3.37	10.9
NH ₂ D		3.5mm	E		
HNCO	Isocyanic Acid	3.36mm/1.4cm	E		
CH ₄	Methane	3.94mm	E	4.46	12.6
H ₂ CS	Thioformalde- hyde	9.56cm	A		
HCOOH	Formic Acid	18cm	E		11.1
HC ₃ N	Cyanoacetylene	3.3cm	E	3.97	11.6
H ₂ C ₂ O	Ketene	2.94/3.0/3.67mm	E		
CH ₂ NH	Methanimine	5.7cm	E		
NH ₂ CN	Cyanamide	3.72mm	E		
CH ₃ OH	Methanol	0.3/1/36cm	E	3.90	10.9
CH ₃ CN**	Methylcyanide	2.72/8.15mm	E	4.76	
NH ₂ COH	Formamide	6.5cm	E		
CH ₃ C ₂ H	Methylace- thylene	3.52mm	E		
CH ₄ CO	Acetaldehyde	9.38/28.2cm	E		10.2
CH ₃ NH ₂	Methylamine	4.1/3.48/34.1mm	E	3.39	9.8
HC ₅ N	Cyanodiace- thylene	2.82cm/1.25cm	E		
H ₂ C ₂ H ₃ CN	Vinilcyanide	2.18mm	E		
CH ₂ CHCN	Acrylonitrile	21.9cm	E		
CH ₃ C ₃ N	Methyl Cianoacetylene				
HCOOCH ₃	Methyl Formate	18.6cm	E		
(CH ₃) ₂ O	Dimethyl Ether	3.29/3.47/9.64mm	E	3.43	10.5
CH ₃ CH ₂ OH	Ethanol	2.86/3.5mm	E	3.90	10.7
HC ₇ N	Cyanohexa- triyne	1.21/1.27/2.94cm	E		
HC ₉ N	Cyano- Octatetrayne	2.86/2.06cm	E		

C) Molecular Ions

N ₂ H ⁺	Protonated Nitrogen	3.22mm	E		
CH ⁺	Methylene Ion	3745/4233 A	A	7.75	14.2
HCO ⁺	Protonated Carbon Monoxide	3.46mm	E		
DCO ⁺	Deuterated Formyl Ion	4.16mm	E		
N ₂ D ⁺		3.9mm	E		

D = Dissociation energy - I = Ionization energy

= Observed also in other galaxies

**= Observed also in Comets

important UV and IR ranges where many molecules (e.g. H_2 , CH_4) have their detectable transitions. Molecular Hydrogen which should be the most abundant molecule in the IM (see Table II) was discovered by UV rocket spectroscopy in absorption against the star ζ Persei and the Copernicus satellite confirmed this discovery in many other stars and also the presence of HD with a ratio HD/H_2 : $1/10^6$. The importance of H_2 detection in the IR range will be discussed later.

One of the most difficult problems for chemists and physicists is to understand molecular formation in interstellar clouds, since it seems that interstellar chemistry favors reactions which lead to the formation of organic molecules and it is possible that the complicated "interstellar laboratory" could produce unknown molecules thus making the identification more and more difficult.

3. FORMATION AND DESTRUCTION OF INTERSTELLAR MOLECULES

As indicated in Table II, the physical conditions in interstellar clouds seem not to be very favorable for molecular formation in the way we are normally used to study this process in the laboratory. Many theoretical models have been proposed and laboratory experiments were started a few years ago with the improvement of new technologies (Cosmovici 1976).

We can summarize here the most probable formation mechanisms in four categories:

- 1.) Collisions between free atoms in the gas phase (two-or three-body collisions).
- 2.) Chemical and physical absorption on interstellar grains with subsequent evaporation of new formed molecules.
- 3.) Formation in cool stellar atmospheres with subsequent ejection in the interstellar space.
- 4.) Formation during the gravitational collapse of a cloud i.e. in the presolar nebula.

We can not say which mechanism could be predominant and in any case a single mechanism would never be efficient for all molecules discovered. The density and the temperature of the objects where the molecules are formed are certainly the determining factor. The reactions in the gas phase (mechanism 1) which can occur and which are known in laboratory are:

- a.) Two-Body collisions: $AB + C \rightarrow AC + B$
- b.) Three-body collisions: $A + B + C \rightarrow AB + C$
- c.) Radiative association: $A + B \rightarrow (AB)_i^+ \rightarrow AB + hv$
- d.) Charge transfer: $A^+ + B \rightarrow A + B^+$

TABLE II

TYPICAL CONDITIONS IN INTERSTELLAR CLOUDS

Density: $10\text{-}10^5/\text{cm}^3$
 Mean free path: $10^{10}\text{-}10^{14}\text{cm}$
 Temperature of atoms: 30-150 K
 Temperature of grains: 10-30 K
 Temperature of electrons: 60 K
 Mean temperature: 100 K
 Diameter of the cloud: 5-40 parsec
 Time between cloud collisions: $10^6\text{-}10^7$ y
 Time between atomic collisions: 1-100 y
 Mass of a cloud: $10^3\text{-}3 \cdot 10^5$ solar masses

CHEMICAL COMPOSITION OF A BIG CLOUD (ABOUT 10^5 SOLAR MASSES)

<u>Atom or molecule</u>	<u>Solar masses</u>
CO	100
H	40
OH	0.78
NH ₃	0.50
CN	0.50
H ₂ CO	0.014
CS	0.014
HCN	0.010

The highest missing mass is probably H₂ with a density of $10^5/\text{cm}^3$.

- e.) Radiative recombination: $A^+ + e \rightarrow (A)_i \rightarrow A + h\nu$
 f.) Dissociative recombination: $AB^+ + e \rightarrow A + B$

(the index i denotes a short unstable state)

For a detailed description of the reactions possible on the basis of the above mechanisms see Cosmovici (1976) and Delgarno (1975).

Once the molecules are formed they are exposed to the destroying radiation of the near stars and their mean lifetime depends upon three parameters: absorption cross section, dissociation probability and interstellar radiation field; the energy density of such a field is about $40 \cdot 10^{-18}$ erg/cm³.

From theoretical calculations on the lifetime of some molecules like CO, CH₄, H₂CO and H₂O it follows that in this interstellar regions (not protected by dense clouds) all molecules considered, with the exception of CO, can not survive more than 100 years. Therefore, if these calculations are correct, molecules can be formed and can survive only in the dense clouds were they are observed, thus excluding the possibility of injection from the atmospheres of cool stars unless they are protected by companion grains during the long travel from star to cloud.

Molecules can also be destroyed by X, gamma and cosmic rays, but these processes are much less efficient than the UV radiation of hot stars and become important only in very dense clouds were the stellar radiation is absorbed by grains.

4. COMETARY MOLECULES

Since comets are believed to be the remnants of interstellar material which escaped from the presolar nebula during gravitational collapse, their molecular content is extremely important for the knowledge of the original components of a collapsing cloud. The physical and chemical properties of the cometary frozen nucleus are unknown and only a cometary mission will give an answer to such a puzzling problem.

All molecules discovered by visible and radio spectroscopy are summarized in Table III. These can be divided in two categories: those evaporated from the nucleus and excited by the solar radiation contributing to the cometary coma and those blown up and ionized by the solar wind forming the cometary tail. The list of molecular ions in the tail is of course limited since observations have been made only in the visible. Other molecular ions have detectable transi-

TABLE III
COMETARY MOLECULES

Coma:

CN, OH, C_2 , C_3 , CH, NH, NH_2 (detected in the visible)

H₂O, HCN, CH₃CN (detected in the radio)

density: 10^{13} - 10^{14} /cm³ at 1 A.U.

Tail:

CO^+ , CO_2^+ , N_2^+ , OH^+ , CH⁺, H_2O^+ (detected in the visible)

density: 10^2 - 10^3 /cm³ at 10^5 km from the nucleus

(the underlined molecules were discovered also in the interstellar medium)

Principal constituents of the nucleus (hypothesis):

H_2O , CH_4 , NH_3 , H_2CO

tions only in the UV and IR range of the spectrum. The radio discoveries of CH_3CN and HCN in Comet Kohoutek could be the first evidence for the interstellar origin of comets. The identification of the first parent molecule, H_2O , in Comet Bradfield supports the Whipple theory that water ices should be the dominant constituents of the nucleus. The search for CH_4 and H_2 has been unsuccessful up to now (Barbieri et al. 1974, Cosmovici et al. 1974).

5. MOLECULES IN COOL STARS

Molecules are present in all stars later than about F 5 and become more prominent in cooler stars such as M 2-M 6.

About a century ago Angelo Secchi made his classification of four types of stars. Only within the past ten years has it been possible to make a quantitative analysis of stellar molecular bands. Data on dissociation and activation energies of molecules as well as vibrational, rotational and electronic levels have been achieved only recently.

Important parameters can be derived from the study of stellar molecules, especially in the IR-range. Among them we can mention briefly (Dirschel et al. 1978; Sprinrad and Wing 1969):

- 1.) The abundance of certain elements can be obtained only from bands of their molecular compounds.
- 2.) Stellar isotope ratios can be investigated mainly with the aid of molecular bands.
- 3.) The R-V bands of polyatomic molecules may be important as an opacity source in the late stellar atmosphere.
- 4.) Dissociation of H_2 may have a profound influence on the structure of the convection zones in late-type stars.
- 5.) At temperatures $T < 3200^\circ \text{K}$ (M2) the blocking of the outgoing radiation in the visible and photographic wavelength range is primarily due to molecular bands.
- 6.) The excitation temperature of a molecule can be determined by studying the vibrational and rotational lines and bands.

If we examine the HR diagram (L versus T), we can observe that the luminosities become so low, when we extend the main sequence to $T < 2000^\circ \text{K}$, that detection and identification of cool dwarf stars become more and more difficult.

The coolest known example among the Mira variables found in this region of the HR diagram is NML-Taurus (1200° K at minimum)(Low 1968).

The Neugebauer survey at 2.2 μ has shown the existence of many red giants, variables and stars reddened by interstellar dust.

During the gravitational collapse of dust and gas clouds when protostars are formed, most of the irradiated energy lies in the IR region. Since stars are formed behind opaque screens of interstellar dust, which become transparent only beyond about 2 μ , they can not be observed as a bright optical event. Therefore we can look at regions of space, where stars are probably in formation, only at IR wavelengths.

A cool extended circumstellar shell containing strong molecular absorption will, of course, shift the spectral energy distribution into the near IR as e.g. in C-stars. Any star which ejects mass continuously will produce a constant supply of material which will be transformed into grains when the temperature decreases; the selective extinction of interstellar dust will shift the observed maximum of the star energy distribution in to the near IR (see e.g. NML Cyg, VI Cyg 12, etc.). The circumstellar dust shells heated to 100° K to 1000° K radiate substantially in the region from 3 to 25 μ .

In order to identify the material in grains, spectral observations are extended to the region between 5 and 8 μ and beyond 25 μ . Double emission peaks observed at 10 and 20 μ are due to silicates bound in grains containing 10^7 - 10^8 atoms. Stellar molecules observed in the IR are :SiO at 4.05 μ (This transition has been observed in all giants and supergiants rich in oxygen of spectral type M and since the SiO bands are a function of the spectral type it could be used in order to classify the most evolved stars.), CO at 4.7 μ , C₂ at 1.767 and 2.5 μ and CH at 2/2.3/3.7 μ . The presence of acetylene at 3.04 and 13.7 μ is not yet sure.

New molecular transitions have also been discovered in the radio region. After the discovery of OH emission in the interstellar space (1968), stellar astronomy was jolted by the detection of very strong OH emission in the IR star NML Cyg. Subsequently many stars have been found to emit the 18 cm lines of OH (Wallerstein 1973). Also H₂O emission at 1.35 cm was found in some stars of late type about M4 or later. These stars show an excess in the IR in the 2-20 μ region, above the radiation which would be predicted by the photospheric effective temperature. Many of the OH and H₂O microwave emission sources associated with IR stars are listed by Wilson (1973).

6. METALOXIDES

Only 12 metaloxides have been identified with certainty in cool stellar atmospheres and sunspots, despite the high cosmic abundance of oxygen. The identification of some alkaline earth oxides like BaO and SrO has been classified as "questionable". Rare earth oxides, with the exception of LaO, have never been investigated in much detail although they are very important as nucleosynthesis indicators. An example is the spectrum of the unique variable star FG Sagittae. This star has been changing in a way strongly suggesting that its atmosphere is becoming contaminated by such heavy elements as Ba, Sr and the rare earth metals, to about 25 times the solar abundance. The enriched elements are those associated with the s-process of nucleosynthesis. In our work (Dirscherl 1978) we have considered the possibility of detecting some alkaline earth and rare earth oxides in sunspots ($T_R \sim 3700^\circ \text{K}$) and in cool stellar atmospheres (2400 to 3000°K) on the basis of dissociation energies, equilibrium constants, cosmic abundances, ionization potentials and physical parameters of the stars. We have calculated the equivalent width of an optically thin rotational line in a metaloxide spectrum absorbing light from the reversing layer of an M 5 star (2500°K):

$$W \sim f_{el} \cdot \frac{\mathcal{G}_{MO}}{\mathcal{G}_M \mathcal{G}_O} \cdot e^{(D-I)/KT} \cdot \frac{K_1 \cdot K_2}{P_e} \cdot \zeta_n \cdot (\zeta_o - \zeta_e)$$

where $f_{el} \sim 10^{-2}$ is the oscillator strength of the transition, \mathcal{G}_{MO} , \mathcal{G}_M , \mathcal{G}_O are the statistical weights of metaloxides metal atom and oxygen atom, D the dissociation energy of the MO , I the hydrogen electron affinity (0.75 eV), K_1 , K_2 the equilibrium constants of the reaction $2 O \rightleftharpoons O_2$ and $1/2 O_2 + H_2 \rightleftharpoons H_2O$, P_e the electron pressure and ζ_i the elemental abundances.

Whereas the statistical weights can be estimated within close error limits (indicated by dashed lines in Fig. 1), reliable values for D have become available only recently for the heavier elements from molecular beam studies (Dirscherl 1978). The solid line in the figure corresponds to the present detection limit of a line of $W = 1 \text{ mÅ}$. Most identified metal oxides are above the line in the region $W > 1 \text{ mÅ}$. Some like PrO, GdO and NdO have not yet been reported even though they should be detectable, if laboratory spectra were available. On the other hand some tentative assignments like the ones of BaO, SrO and MnO are probably erroneous.

The most important conclusion is that lowering the detection limit e.g. by Fabry-Perot-techniques (Barbieri et al. 1974; Cosmovici et al. 1974) would make possible the quantitative

evaluation of many further metal oxides, out of which only a few are shown in the figure. Among these elements, most are associated with the s-process of nucleosynthesis and are enriched, at least in several isotopes, with respect to the solar abundances in late type stellar atmospheres. The radiation maximum of such stars lies around 1 micron and so the requirements for improvement of the spectral resolution lies in the near IR range (Michel 1974).

7. THE IMPORTANCE OF FUTURE IR OBSERVATIONS

Most astronomical problems can benefit substantially from infrared astronomy, especially the field of molecular research (e.g. cool stars: H_2O , CH_4 , NH_3 , CO_2 , CO). One of the most important problems in the near and middle IR is the study of reddening in cool stars, since this allows the direct determination of the extinction curve of stellar light in the high wavelength region of the spectrum.

The extinction curve permits one to determine the true stellar intensity corrected for absorption due to interstellar matter thus leading to more accurate stellar distances when the absolute magnitude is known. Recent results suggest also that stellar distances and consequently the dimensions of the galaxy could have been overestimated. We will summarize here the most important points for encouraging infrared astronomy, especially in space (Michel 1974):

- 1.) The range of sight within the galactic plane is much larger than in the visible. For example, the galactic center can be observed easily.

- 2.) Especially cold sources ($20 < T_{\text{eff}} < 1000^\circ \text{K}$) can be seen in the range $150 < \lambda < 3\mu$, such as interstellar and circumstellar dust clouds, as can line emitters (ions, atoms, molecules) in H I regions.

- 3.) Different layers in the solar and stellar atmospheres can be probed because the continuum opacity varies roughly as λ^2 and the spectrum is only slightly blended by lines.

- 4.) Small column densities of line emitters are more easily detected in the IR than in the radio region since the transition probabilities for dipole radiation varies as λ^{-3} (fine structure of molecular rotational lines) and those for electric quadrupole radiation as λ^{-5} (H_2). Polyatomic molecules without dipole moments such as CH_4 and CO_2 can radiate in the infrared because of their asymmetric vibrations.

- 5.) Some strong transitions e.g. of He, C, P, S happen to be in the near IR and the corresponding radiation contributes to the analysis of stellar atmospheres.

6.) Since solar light is scattered in the earth atmosphere according to λ^{-4} , even day-light observations are possible and also near-IR observations, especially of comets, can be made with ease if the objects are close to the Sun (Barbieri et al. 1974; Cosmovici et al. 1974).

The most interesting molecule for present and future IR observations is certainly H_2 . Hydrogen is the most abundant element in the Galaxy, as 21 cm observations have shown. Since this radio line becomes weaker in the proximity of dense clouds, it has been suggested that hydrogen will be transformed in H_2 on interstellar grains and that in the coolest regions of the Galaxy H-atoms should be captured by grains, forming a shell of solid hydrogen around the grain. If these hypotheses are correct, atomic hydrogen would represent only a small percent of H_2 and the suggested matter content of our galaxy based on atomic hydrogen would certainly be underestimated.

H_2 can radiate lines in the middle and far infrared (17/28.2/42/84 μ), because of collisional excitation (Field et al. 1966). We do not really know the most probable line transition since the probability of line emission depends upon the density and temperature of gas, parameters which are up to now not well known. Forbidden transitions which are not reabsorbed are of course favored. If the density of a cloud is high enough to start a gravitational collapse to a protostar, from one side IR emission will be determined by the temperature and efficiency of the embryo star, from the other side by H_2 -lines excited collisionally. In order for gas to contract, the gravitational energy must exceed the kinetic gas energy: therefore the gas must be sufficiently dense and cold. For an H_2 -gas the collapsing conditions are: $\rho = 60/\text{cm}^3$ and $T = 50$ K. Thus at 60 μ we will have a maximum of the protostar blackbody radiation. Otherwise many H_2 -forbidden transitions could take place with subsequent IR-emission from the protostar ($T = 100$ -1000 K) and subsequent cooling.

Another reason to search for molecular hydrogen emission at longer wavelengths is that this IR-light penetrates better through dust clouds. Shock-compressed shells around early-type stars hidden in molecular clouds can be detected; there are also indications from recent IR measurements around 150 μ that hidden stars are, indeed, quite frequent.

Since band transmission and thermal emission of the earth's atmosphere restricts ground based observations to a few windows (given in Table IV) at $\lambda < 25 \mu$ and another at 350 μ , the future of this new branch of modern astrophysics will depend on space

TABLE IV.

USABLE ATMOSPHERIC WINDOWS FOR IR GROUND OBSERVATIONS

Photometric designation	$\lambda(\mu)$	HW (μ)	Absolute flux (W/cm^2)
J	1.25	0.38	$3.4 \cdot 10^{-13}$
H	1.62	0.22	$1.28 \cdot 10^{-13}$
K	2.20	0.64	$3.9 \cdot 10^{-14}$
L	3.40	0.90	$7.1 \cdot 10^{-15}$
M	5.0	1.20	$2.0 \cdot 10^{-15}$
N	10.2	6	$1.3 \cdot 10^{-16}$
Q'	22	7	$7.7 \cdot 10^{-18}$
Q''	20	7	$1.1 \cdot 10^{-17}$

technology (Michel 1974, Hoffmann 1972, Low 1968, Spinrad and Wing 1969). Up to now only airplane and balloon observations, up to 40 km, have been carried out but no molecular transitions have been detected yet in the IR from extraterrestrial sources. An enormous amount of data from broad-band and high resolution IR spectroscopy has to be expected in the next ten years from IRAS-satellite, Spacelab and the Space Telescope (Hoffmann 1972; Barbon et al. 1977).

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DISCUSSION

Cowley: Are the dissociation energies of the lanthanide oxides reliably determined?

Cosmovici: We could measure in our molecular beam apparatus dissociation energies with the highest accuracy up to now (1%) for SrO, YbO, and EuO. Other dissociation energies are affected by an error of 10-20% and are measured by flame spectroscopy methods or chemiluminescence. For details see: Dirscherl, Michel and Cosmovici, 1978, Astron. and Astrophys., 68, 381.