SOLAR SYSTEM RADIO ASTRONOMY

Dave Buhl

I. MOON (Diameter = 30')

The radio emission from the Moon has a mean temperature of $\sim 200°$ K plus a 29.5 day sinusoidal variation whose amplitude decreases with greater depth into the lunar surface. The depth of penetration is proportional to the radio wavelength and therefore, by comparing the phase and amplitude of the diurnal variation at different wavelengths, some information about the bulk properties of the lunar surface layer can be obtained.

Infra red observations of a Lunar Eclipse have revealed a rapid temperature decrease for most regions ($400°$ K $\rightarrow$ $200°$ K). This indicates a very porous insulating surface. Numerous bright rayed craters have enhanced thermal emission during the eclipse, being as much as $50°$ K warmer than their surroundings. Several of the Lunar Maria also exhibit an elevated temperature of $\sim 5°$ K.

Radio observations of the Moon at $\lambda = 2$ cm (depth $\sim 1/2$ m) have revealed departures from the diurnal temperature variation of $\sim 5°$ K for several of the Maria. However, no signficant departures were observed for the bright rayed craters. These results suggest that the origin of the thermal anomalies in the craters is the large boulders and surface roughness of these relatively young craters. The Mare anomalies are the result of a relatively dense surface material probably due to lava flows. Presumably this Mare filling followed the gigantic impact which left behind the Mascons buried in the Mare basins.

Radar observations ($\lambda = 3.8$ cm and 68 cm) show strong reflections from the very young crater Tycho and smaller returns from the other craters and

and Maria. This fits into the general picture of a rough rocky surface for the bright rayed craters and large areas of dense material filling the Mare basins.

II. VENUS (Maximum Diameter 1')

Because of the cloud layers on the planet Venus, the lower atmosphere and surface are only accessable to radio and radar observations or satellite probes. Radio observations at λ = 6 cm give a maximum temperature of 650 ° K with a decrease at longer and shorter wavelengths. This value of 650° K is assumed to be the surface temperature. The decrease at shorter wavelengths is due to the increasing optical thickness of the atmosphere. At the water vapor line wavelength of 1.35 cm the main emission is coming from an altitude of 50 km, still well below the cloud layer. Accurate measurements of radio temperature of Venus around this wavelength would settle the question of how much water vapor there is in the Venus atmosphere.

Interferometer observations of Venus at λ = 11 cm have been used to determine the diurnal temperature variation of the surface of the planet. This variation is only 18° K between the day and night sides. Since the day on Venus is 243 Earth days, there must be considerable heat transport in the lower atmosphere of Venus to allow this small a temperature difference. In addition, very little cooling of the poles is observed. Since the surface pressure is 100 atmospheres, these conditions are quite reasonable.

Radar observations of Venus have determined that the rotation of the planet Venus is retrograde with a possible lock to the Earth's orbit. A number of features have been identified on the surface, but a map of the surface will probably require a bistatic radar experiment using a satellite orbiting about the planet. A combined radar satellite experiment has already yielded a very accurate radius for Venus of 6053 km.

III. MERCURY (Maximum Diameter 12")

A very hot Moon-like planet, Mercury has been shown by radar measurements to have a synchronous rotation period equal to 2/3 its orbital period. Radio measurements at various wavelengths and infra-red observations indicate a very porous surface with some radiation conductivity in the upper layers.

IV. MARS (Maximum Diameter 6")

Mars appears to have seasons like the Earth with developing and receding polar caps of CO_2 frost. Surface temperature is between 200° K and 300° K with a rotation period about the same as the Earth's.

Surface pressure is 1/100 atmosphere providing little heat transport or protection from solar UV. As a result it is unlikely that the seasonal variation in the color of the light and dark areas is due to some form of plant life. Altitude variations as determined from CO_2 densitites are rather large ($\sim$ 10 km.). There appears to be no volcanic activity at present and a large number of crater basins can be seen in the Mariner photographs.

V. JUPITER (Maximum Diameter 40")

Low frequency radio emission from Jupiter (10 - 100 MHz) contains very large bursts apparently associated with the satellite Io. When the satellite is 90° to the Earth-Jupiter line the maximum number of bursts occurs. This is thought to be the result of Io pulling a section of the magnetic field of Jupiter through the plasma in the Van Allen belts, and creating a dynamo which dumps large currents at the planets surface near the poles.

Radio emission at λ = 11 cm is primarily synchrotron from the high energy particles in the Van Allen belts. This appears as a dumbell centered on the planet and extending $\sim 2'$ on either side perpendicular to the magnetic axis. The belts rock back and forth in the 10 hour rotation period indicating a tilt of 10° between the magnetic axis and the rotation axis. There is also apparently an assymetry in the belts which rotates with the planet. Further interferometer and polarization measurements of Jupiter will help clarify the geometry of the magnetic field and high energy particles.

Short wavelength radiation from Jupiter is primarily thermal emission from the 150° K planet. Emission in the range 20 - 30 GHz exhibits the shape of the ammonia bands, which is a major constituent of the atmosphere.

VI. SATURN AND THE OUTER PLANETS (Diameter less than 20")

No radiation belts have been detected for Saturn. Recent infra-red measurements of Saturn's rings have shown a spectral band which could be ammonia or water frost.

Uranus and Neptune have been detected in the 3 mm to 10 cm range but very little is known about these planets.

VII. SUN (Diameter = 30)

Solar burst emission at long wavelengths can be classified into various types depending on the duration, direction of frequency drift, polarization and intensity. Bursts are apparently related to flares in active regions. It is thought that shock waves in the lower solar atmosphere propagate upward and cause plasma bursts in the upper atmosphere. Large bursts are usually accompanied by particle emission in the solar wind along the magnetic field lines which probably extend at least as far as Jupiter, 5 AU from the Sun.

Short wavelength emission is slowly varying and associated with bright plage regions seen in Hα. Occassional flaring can be seen over a period of several minutes to hours. At λ = 3 mm the emission originates from $\sim$ 5,000 km above the photosphere and in active regions is 100° K to 700° K hotter than the quiet Sun. Cool regions are observed which appear to be coincident with filaments in H α. They are sometimes observed several days before the appearance of a filament because the optical depth is greater at 3 mm than in H α. The general structure is stable over several days and probably over several 27 day rotation periods of the Sun.

The radio spectrum of the quiet Sun has a constant temperature of 6000° k up to a wavelength of 3 mm and then increases slowly to 9000° k at $\lambda = 2$ cm and then sharply upward to 10^5° k at 30 cm. Since the altitude of emission from the atmosphere increases with increasing wavelength, these radio wavelength measurements help to define the models of the solar chromosphere.

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Light Molecules and Dark Clouds

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The interstellar medium, which consists of vast clouds of gas and dust mingled among the stars of our Galaxy, has long been a major subject of interest to radio astronomers. Partly this is because the resolution and sensitivity of radio telescopes have not been sufficient to detect normal stars. Optical astronomers from the days of William Herschel have been aware of dark nebulae which were originally thought to be holes in our Galaxy. We now know that these regions do not represent a lack of stars, but are actually large obscuring clouds of dust which prevent us from seeing the background stars. Many of these regions have been cataloged by Barnard and Bok and Lynds and Heiles. Sometimes associated with these dust clouds are bright nebulae of ionized hydrogen called HII regions. These clouds generated considerable interest because it is believed that here is where stars are being formed.

The great nebulae in Orion is the best example of this type of cloud. It consists of a bright wispy nebulae in front of a very dense dark cloud. Astronomers have detected several infrared objects in the center of this cloud. These may represent young proto-stars or condensations during a very early period in the evolution of a star. Many similar regions probably exist in our Galaxy but cannot be seen because of the obscuring dust. This dust severely limits optical astronomers when they try to look into the disk or plane of our Galaxy.

However, radio astronomers are little affected by this dust and can study the Galactic plane quite easily. As an example of what a radio astronomer sees when he points his telescope toward our Galactic center, study the formaldehyde (H_2CO) spectrum. This contains a remarkable number of features. Each of these valleys or absorption lines represents a large cloud of gas moving away from us (positive velocity) or moving toward us (negative velocity). Such a spectrum of a molecule seen against a bright radio source has its analog in optical absorption lines seen in the spectra of bright stars which are produced by intervening interstellar molecular clouds. These lines are also blue or red shifted, the color change produced by the motion of the cloud which doppler shifts the fundamental wavelength of the line.

Although radio astronomy can produce remarkable spectra and determine velocities of individual clouds extremely accurately, its ability to produce photographs of a portion of the sky is limited. This is due to poor resolution (one minute of arc with the best telescope) and the lack of anything equivalent to photographic film to retain the image. As a result pictures or maps of a radio source have to be painstakingly built up one dot at a time with a single telescope (in the future interferometers such as the Very Large Array will provide a radio picture with an eight hour exposure and one second of arc resolution). The distinct advantages of the radio region of the spectrum become clear when we consider molecular lines.

Molecules, like everything else in nature have certain resonances, and in particular these resonances are quantized or occur at specific frequencies. For a molecule these originate from rotations of the molecule about various axes, vibrations of the various atoms against each other and electronic resonances due to the orbits of the electrons about each nucleus. Roughly the frequencies of rotational transitions are in the microwave or radio range of the spectrum, vibrational transitions in the infra-red and electronic transitions in the optical. At this point we must also realize that the resonant frequency of a molecule which is observed is really a transition from one energy level to another. In other words the molecule is rotating away at a particular energy level and suddenly slows down dropping to another energy level and emitting a photon whose frequency is related to the energy difference. This is generally represented by an energy level diagram in which the quantized energies of the molecule are plotted in reciprocal wavelength ($1/\lambda$ in cm^{-1}). In this representation the observed frequency is very easily obtained by the difference between the upper and lower levels of the transition. Hence the line which we observe being produced by a molecule is actually the difference between two energy levels of the molecule. The energy level diagram for each individual molecule is quite different. The net result is a specific frequency by which we can identify a particular molecule and this is a very valuable tool for the astronomer.

The shorter wavelengths always require more energy and another critical factor in making a molecule resonate is the question of excitation. The higher the energy level the more excitation is required: the number of wave numbers (cm^{-1}) above the ground state is approximately equal to the temperature required to excite the transition. A temperature of 100°K will excite all the levels up to 100 cm^{-1}. In the formaldehyde (H_2CO) energy level diagram it can be seen that 25°K is sufficient to excite all the transitions that have been found in the radio range of the spectrum. Alternately transitions in the infra-red and optical range require much higher temperatures or excitation energies.

But where does this discussion of quantum levels leave us in the real universe. Two basic principles emerge: (1) molecules have distinct characteristic frequencies by which they can be identified and, (2) for temperatures normally encountered in molecular clouds (3°K to 200°K) the main excitation of the molecule is in rotation which corresponds to frequencies in the radio range of the spectrum. A third and more subtle point is that the overlap of lines in the radio range is very small compared with the infra-red and optical regions. What this means is that a molecule like formaldehyde was identified initially by one radio line with 99% certainty. Presently nine lines from the formaldehyde molecule have been identified.

Although radio observations have been enormously important in unraveling the mysteries of interstellar clouds, the very earliest detection of molecules came from the optical observations of Dunham and Adams at Mt. Wilson. Their observations with the 100 inch telescope showed several lines in the spectra of stars which appeared to be interstellar. The subsequent identification of these interstellar lines as CN, CH and CH^+ by McKellar, Swings and Rosenfeld, and Douglas and Herzberg was the first evidence of the chemical nature of interstellar clouds. Recently Carruthers has identified molecular hydrogen (H_2) in the ultraviolet spectra of one star using a special UV camera he designed (see Mercury for March 1972). In 1936 Merrill found several optical diffuse bands. This discovery has resulted in a considerable amount of controversy over the years as to the origin of these diffuse lines. The most recent proposal is a suggestion by Johnson that these may be due to a porphyrine molecule. However, the existence of unidentified lines is not peculiar to optical wavelengths, as will become evident in our discussion of the radio observations.

Except for the detection of the very important 21 cm line of atomic hydrogen and the recombination lines of ionized hydrogen, not very much happened during the next 25 years to illuminate the chemical composition of interstellar clouds. During the late 50's some unsuccessful attempts were made to find hydroxyl (OH) using a frequency calculated for this molecule. The development of the autocorrelation receiver and a measurement of the frequency led to a successful detection in 1963 by Weinreb, Barrett, Meeks and Henry. Although initially found in absorption against the strong radio source Cassiopeia A, the most spectacular discovery didn't come until two years later when groups at Berkeley and Harvard simultaneously found very strong emission lines which defied explanation. Harold Weaver was inclined to call the lines mysterium because of their very narrow widths and peculiar intensities. It was not until sometime later that the idea of an interstellar maser took hold. A maser is a means by which a large number of molecules can act as an amplifier at their resonant frequency. In this case the hydroxyl (OH) cloud becomes a giant amplifier producing very intense lines. It is interesting at this point to relate that Charles Townes won his Nobel prize for his discovery of the laboratory maser. He also played a very important part in the subsequent development of molecular line radio astronomy.

The stage was now set for the main assault on molecular clouds which began in 1968. The opinion of most astronomers at this time held that because of the low densities which existed in the interstellar medium it would be very difficult to get more than two atoms together at one time. Thus only diatomic molecules were to be expected and even these would be short lived due to the harsh environment created by high energy cosmic rays and ultra violet light. Because of this prevailing opinion no one attempted to search for more complicated molecules. What was overlooked was the important role of dust grains in producing and protecting the molecules from destruction.

Then in 1968 two groups began to make plans for molecular expeditions which required not only the use of good short wavelength radio telescopes, but also spectral line receivers with very stable local oscillators so that any lines detected would not be blurred by changes in this reference oscillator. At Berkeley: Townes, Welch, Cheung, Rank and Thornton began to assemble equipment and a new 20 ft. millimeter wave antenna to look for ammonia (NH_3) at a frequency of 23.8 GHz; while at the National Radio Astronomy Observatory: Snyder and Buhl were making similar preparations to find water (H_2O) at a frequency of 22.2 GHz. The ammonia molecule is much easier to excite while the water molecule is more obvious from the chemical standpoint given the presence of H and OH. The Berkeley group was able to get their equipment into the field first and as a result in late 1968 they detected both molecules since the frequencies are quite close. This was a rather exciting competition with most astronomers betting that both groups would lose. The ammonia was detected in several lines, while the water which only has one line showed a rather surprising maser emission even more intense than the OH.

One of the interesting properties of a maser is that it can transfer energy, i.e., the kinetic energy or heat in a hydrogen cloud can be transferred to radiant energy at infra red or radio wavelengths. This is very important when a hydrogen cloud is collapsing to form a new star. The energy in the cloud can be used to excite a water maser which will radiate away the energy; thus cooling the cloud and allowing it to continue collapsing. This is precisely what the observations of water clouds seem to suggest. Their sizes are extremely small, Very Long Baseline measurements give a few Astronomical Units or solar system dimensions for the water emission. The amount of energy is quite enormous, within a few orders of magnitude of the energy radiated by our own Sun at all wavelengths. The maser funnels all this energy generated by the collapse into one narrow radio line. All of this leads to the conclusion that the masers are clouds of hydrogen and molecules collapsing and giving birth to stars.

Spurred on by the importance of these results the NRAO group in collaboration with two other astronomers (who had done graduate work on OH at Harvard under Edward Lilley) began a search for formaldehyde (H_2CO). The four of us: Snyder, Buhl, Zuckerman and Palmer detected a very strong absorption line in practically every radio source we looked at. The excitement over the fact that not only had this complex molecule been found but that it appeared to be a very common part of our galaxy is now hard to imagine. Today we accept as routine another large interstellar molecule being found, but three years ago the formaldehyde result was really incredible. Particularly when you consider that the water and ammonia lines were found in only a very small number of radio sources.

Following quickly were two more astounding results which are still the cause of much debate. First formaldehyde was looked for in a number of nearby dust clouds where hydroxyl (OH) had been found in weak emission lines by Heiles. The startling result of the formaldehyde search was that we found an absorption line! These dust clouds are not radio sources and so we had not expected this, there being no radiation to be absorbed. The only explanation left open was that these clouds of formaldehyde were absorbing the faint 3°K background radiation which is supposed to be the remnant of the primeaval fireball left over from the Big Bang origin of the universe. This radiation permeates all space and produces the faint background against which these clouds are observed. This means that the formaldehyde molecules are <u>cooled</u> below 3°K, a complex process still being debated by Townes and Cheung vs. Thaddeus and Solomon.

The second result was an abnormally high abundance of the carbon-13 isotope of formaldehyde at about ten times accepted solar system values. This meant either extremely high amounts of C^{13} or very dense clouds in which the normal line is completely saturated. Subsequently, several other molecules have shown this same tendency. Although the interpretation is still open to considerable controversy the result is very important as it will indicate the extent to which nuclear burning in massive stars has altered the element the abundances in various parts of our galaxy. Molecules made out of local material would be expected to reflect any change in these abundances. Resolving this problem requires high resolution observations with spectral line interferometers to determine the size and density of molecular clouds. These questions will be answered by the Very Large Array leaving only a small residual of doubt. Thus ended the year 1969 with the detection of only one molecule, the incomparable formaldehyde.

The next important step required the development of receivers which would operate in the very short 2-4 millimeter wavelength range. Molecular line receivers were difficult enough to build at 23 GHz for the water and ammonia lines. The design of a receiver to operate at frequencies over 100 GHz was the result of considerable research at Bell Telephone Laboratories and a co-operative development project with NRAO. Schottky barrier mixers were made by Burrus of BTL using very small area diodes in a Sharpless mixer. Penzias, Wilson and Jefferts of BTL along with Weinreb of NRAO worked out the receiver design. This receiver was used on the NRAO 36 ft. telescope and resulted in the important detection of carbon monoxide (CO) and cyanogen (CN) in April 1970. The contributions of these five people to the cause of molecular astronomy should not be underestimated. Using the receiver they developed, the mm-wave region of the spectrum has yielded about half of the molecules which have been found in interstellar clouds.

The carbon monoxide (CO) molecule is an extremely tightly bound molecule, and proves to pervade much of our Galaxy. The claim by BTL that this line will replace the 21 cm hydrogen line for studies of Galactic structure should be taken very seriously. Apparently the carbon oxygen ($C \equiv O$)bond is dominant in nature with formaldehyde (H_2CO) and methyl alcohol (CH_3OH) being important examples.

The detection of the hydrogen cyanide (HCN) molecule in June of 1970 by Snyder and Buhl brought in another strongly bonded molecule which appeared to be widely distributed in our Galaxy. At about the same time Turner found a centimeter wave line due to cyano-acetylene (HC_3N). Somewhat later that year Thaddeus, Wilson, Kutner, Penzias and Jefferts, (a group which has evolved into a rather distinguished crowd) came up with three new lines of formaldehyde (H_2CO) at 150 GHz demonstrating the presence of this molecule in the Orion nebulae, a cloud that was strangely missing in our original formaldehyde studies. These three molecules (H_2CO, HCN and HC_3N) are very important in the organic synthesis of amino acids. Recently Cyril Ponnamperuma's group has determined that there are extra-terrestial amino acids in the Murchison meteorite. Why this excitement over organic molecules? Well these particular molecules play a very significant role in studies of the origin of life. Hence the very great interest in these ancestors of life in the universe.

An experiment of major importance to our present narrative occurred in 1953, when Miller and Urey showed that amino acids of various types were produced when an electrical spark was discharged in a mixture of water (H_2O), ammonia (NH_3) and methane (CH_4). The molecules which seem to be most important in these chemical reactions are HCN, H_2CO and HC_3N. The significance of this similarity between laboratory organic molecules and the composition of interstellar molecular clouds is that we may be well on the way to discovering a universal chemistry. If life in turn is based on fundamental laws of chemistry, then life itself is also universal. Therefore, astronomical observations of the evolution of molecular clouds may shed some light on the early chemical evolution of life, particularly since these clouds appear to be the regions of our Galaxy where stars are being born.

Most of the large molecules have been detected solely in the center of our Galaxy, such as formamide (NH_2CHO) discovered by Rubin, Flygare and Swenson. There is a general feeling that this is not the only place where the heavy molecules are being made, but it is the only place where there is a sufficient quantity to be detected. Jefferts of BTL has developed a cooled mixer receiver for the carbon monoxide (CO) line and a research program on applying this idea at 3 millimeters wavelength is being pursued by Weinreb and Kerr of NRAO. This new technique promises to increase sensitivity by over a factor of ten at these wavelengths. A number of heavy molecules have frequencies in this region of the spectrum and so we expect a large increase in the molecular list in the next few years due to this new receiver. In addition, high resolution interferometers such as the Very Large Array and a millimeter wave interferometer being developed by Jack Welch at Berkeley will allow us to make detailed pictures of the molecular clouds.

Unidentified lines are becoming more common in the radio frequency spectrum. The first one was called X-ogen and was found by Buhl and Snyder while pursuing hydrogen cyanide (HCN). Possible molecules or radicals which may be responsible for this line are HCO^+ or CCH. Another line which we also found is tentatively identified as HNC, a hitherto unknown isomer of HCN. There are also several other unidentified lines which have been found by other groups but remain unpublished.

The original detection of methyl alcohol (CH_3OH) by Ball, Gottlieb, Lilley and Radford made use of a low frequency line at 835 MHz. Subsequently Barrett and Schwartz found several lines of this molecule at 25 GHz and recently Turner, Zuckerman and Palmer have found additional lines at 90 GHz. Elaborate models of the excitation of alcohol are being built and the pursuit of interstellar alcohol in its various forms is continuing relentlessly.

Although the astronomical endeavors I have tried to chronicle have been a bit disorderly, they have greatly improved our understanding of our own Galaxy over the past three years. Perhaps some of these observations will even suggest answers to the elusive question of the origin of life. It is intriguing that this magnificent mixture of molecules is present precisely in those parts of our Galaxy where stars and planets are being formed. These molecules help to cool the collapsing hydrogen cloud during the early contraction of the star. They also provide the gases for the primitive atmospheres of the planets as well as the organic ices to make up the comets which circle the star. The life that arises spontaneously on the planet may have its origin in the organic debris from the interstellar cloud or in the volcanic gases erupting from deep within the planet or maybe even from the collision of a large comet resulting in a sudden concentration on the planet of primordial organic material. A number of biochemists have studied this problem starting with Oparin and Haldane and now including Miller, Ponnamperuma, Oro, Orgel, Sagan and others. Through this combination of astronomy and biochemistry we may someday be able to understand the intricate relation between the evolution of an interstellar cloud into stars and planets and the evolution of life on those planets.

For further reading:

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Formaldehyde (H_2CO) Spectrum:

The center of our Galaxy as revealed by the formaldehyde (H_2CO) molecule. The absorption lines or valleys at negative velocities reveal a number of intervening spiral arms between us and the Galactic center. The line at zero velocity is our own local gas while the wide deep feature at +40 is at the Galactic center. Most molecules show this +40 feature but only two (OH and H_2CO) exhibit the other diverse lines.

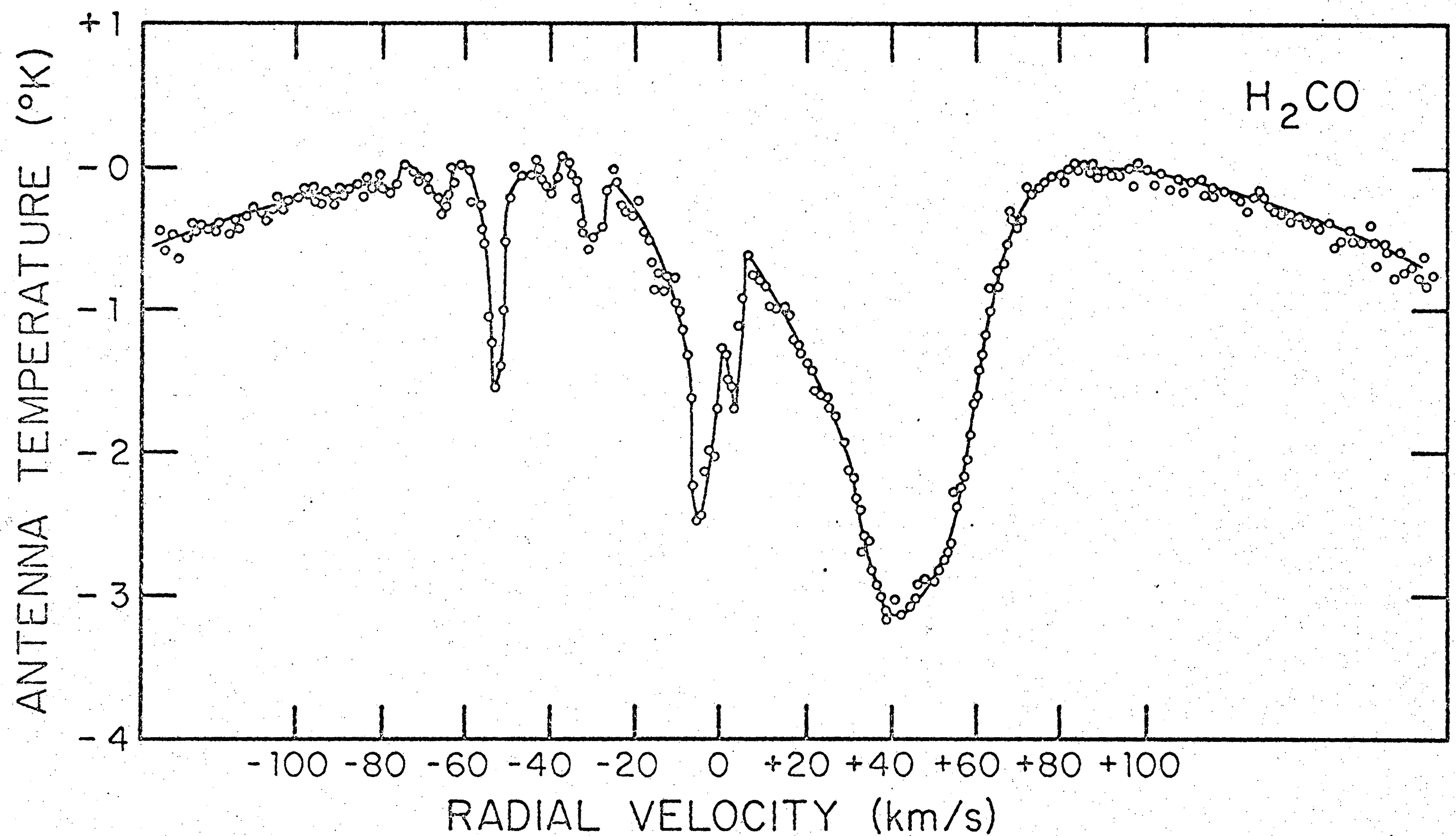
H_2CO Energy Level Diagram:

The three absorption lines of formaldehyde (H_2CO) which have been found are indicated by the heavy black bars while the four emission lines are shown by the dotted lines. The energy level of the molecule (in cm^{-1}) can be taken as the temperature required to get the molecule rotating at that level. Lines are always produced by a transition from one energy level to another. Each level is marked with its appropriate quantum numbers.

Molecule Table:

Molecule population of interstellar clouds. The line intensity is the maximum antenna temperature which has been observed. The number of lines gives the reliability of the identification, but more important indicates the usefulness of the molecule for astrophysical measurements. The list is in order of increasing number of atoms.

Molecule		Line Intensity	Number of Lines
	H_2, CH, CN	Optical	Several
Hydroxyl	OH	200°K	8
Carbon Monoxide	CO	50	3
Cyanogen	CN	1	2
Carbon Monosulphide	CS	2	1
Silicone Monoxide	SiO	0.5	1
Water	H_2O	2000	1
Hydrogen Cyanide	HCN	10	2
X-ogen	HCO^+ or CCH	5	1
Hydrogen Isocyanide	HNC	1	1
Carbonyl Sulphide	OCS	1	1
Ammonia	NH_3	5	4
Formaldehyde	H_2CO	5	9
Isocyanic Acid	HNCO	2	2
Cyano-acetylene	HC_3N	1	2
Formic Acid	HCOOH	0.05	1
Methyl Alcohol	CH_3OH	2	12
Acetonitrile	CH_3CN	1	4
Formamide	NH_2CHO	0.2	3
Acetaldehyde	CH_3CHO	0.2	1
Methyl-acetylene	CH_3C_2H	0.2	1


H2CO
ANTENNA TEMPERATURE (°K)
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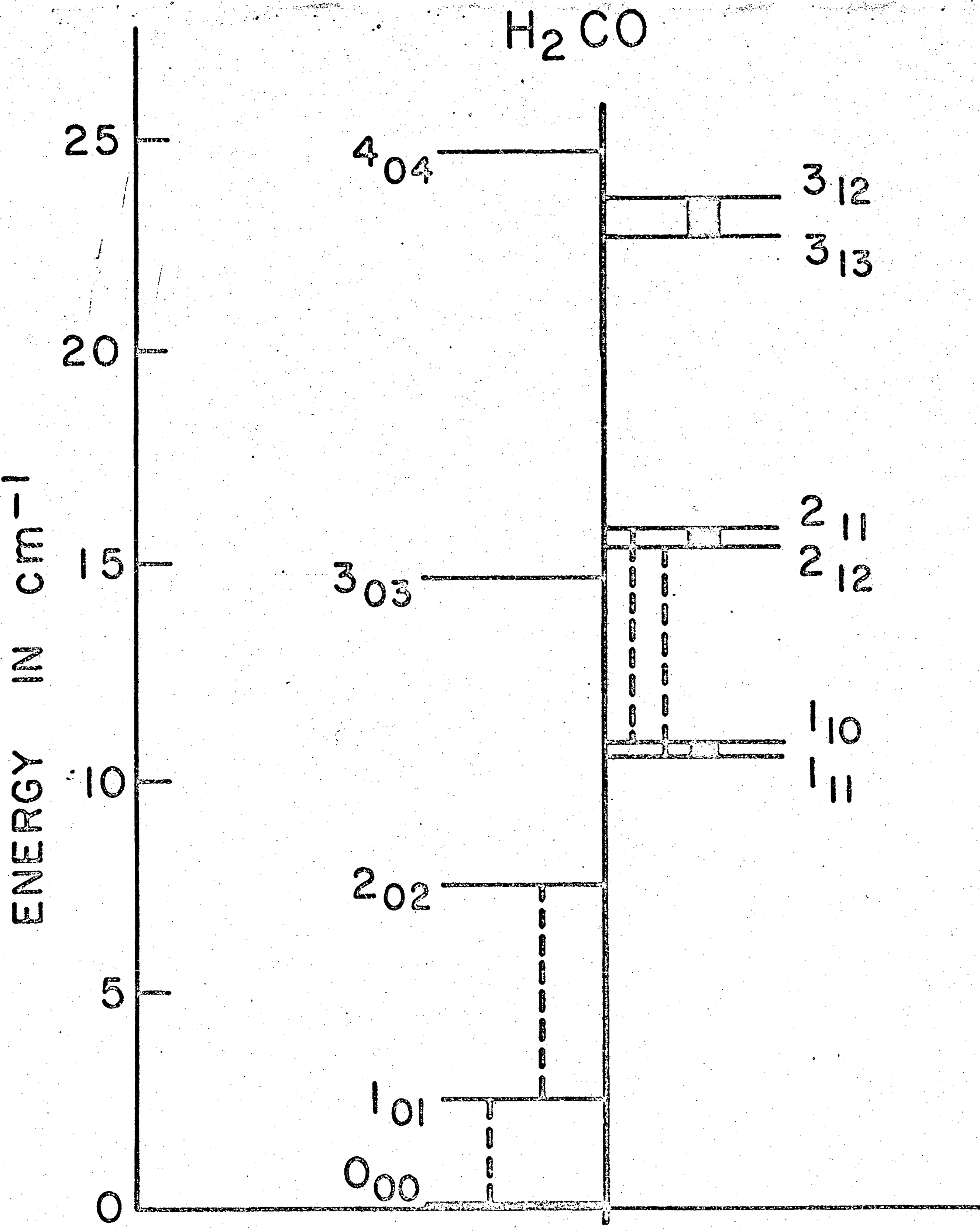
-1
-2
-3
-4
-100 -80 -60 -40 -20 0 +20 +40 +60 +80 +100
RADIAL VELOCITY (km/s)



H2CO
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20
15
10
5
0
404
312
313
211
212
303
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111
202
101
000