Radio Observations of Interstellar Hydroxyl Radicals

Have we discovered a gigantic maser, or could we be detecting interstellar communications?

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On the night of 15 October 1963 a discovery was made which marked the beginning of a new phase of radio astronomy and which, so far, has provided some baffling problems for both the observer and the theoretician. Each new series of observations, intended to clarify a previous set of data, has only served to compound the mysteries. The discovery was the detection of small absorptions of radio emission from the strong galactic radio source Cassiopeia A, at specific frequencies, and attribution of the absorptions to the hydroxyl (OH) radical in interstellar space. The observations were made by a Massachusetts Institute of Technology team of radio astronomers and engineers, which included S. Weinreb, M. L. Meeks, J. C. Henry, and myself; they were carried out at the Millstone Hill Observatory of Lincoln Laboratories, Massachusetts Institute of Technology (*1*).

Radio astronomers had been studying the well-known 21-centimeter spectral line of atomic hydrogen (H) since 1951, but all attempts to detect other radio lines, including an attempt in 1956 to detect OH (*2*), had been negative. Therefore, when the detection of OH was announced to the scientific community there was considerable interest on the part of other observatories in repeating the observations at an early date. The confirmations were quick in coming. One group in Australia (*3*) and two in the United States (*4, 5*) succeeded in detecting interstellar OH within 4 to 6 weeks after the initial October observations. The Australian group detected OH absorption in the radio spectrum of the galactic-center radio source, Sagittarius A; their geographical location precludes observation of Cassiopeia A.

Following the discovery of OH in the interstellar medium, it was possible to envision extensive research programs based upon comparative observations of the H and OH radio spectral lines. The potential existed for (i) mapping the spatial distribution of OH throughout the galaxy, in a manner analogous to the procedure used in the case of H, and, from this mapping, for inferring the distributions of other, similar molecular species; (ii) establishing the OH/H abundance ratio in different regions of the galaxy and possibly relating this to galactic or stellar evolution; (iii) studying correlations between OH, H, and dust in interstellar clouds; (iv) detecting isotopic species of OH, such as $O^{18}H$; (v) gaining information on the O^{16}/O^{18} galactic distribution which would provide insight into the processes of element generation in stellar interiors; and so forth. But these noble goals are still distant. It is a fact, unfortunately, that in slightly over 3 years of studying OH, very little, if any, well-established astrophysical information has resulted. In its place there exists a large body of observational data which clearly indicates that we are observing a very complex phenomenon, not well understood and, until now, not known to exist, under astrophysical conditions. The observational data are rich in information about some astrophysical process, but to extract that information we must first identify the process and understand the origin of its intense radio emission.

To illustrate the nature of the complexity of the OH observations, and to place this review in proper prospective, it is necessary to digress briefly, into the realm of molecular physics. As one would expect, the OH molecule, with an atomic system more complex than that of simple H, has a more complex radio spectrum. What has often been referred to as "the OH line" is, in reality, four lines closely spaced near 1666 megacycles per second (18-centimeter wavelength), and the results of studying each of these lines separately in the interstellar medium has produced some of the puzzles that exist today.

Hydroxyl-Radical Energy Levels and Transitions

Molecular internal energies are generally characterized as being of three types: (i) electronic, associated with the motion of electrons in various orbits, with energy changes giving rise to visible or ultraviolet radiation; (ii) vibrational, due to nuclear vibrations, with energy changes giving rise to infrared radiation; and (iii) rotational, corresponding to the end-over-end rotation of the entire molecule, with energy changes typical of microwave radiation. Since OH is a relatively light molecule, its rotations are very rapid, so that its pure rotational spectrum lies at submillimeter wavelengths. However, because of the physical structure

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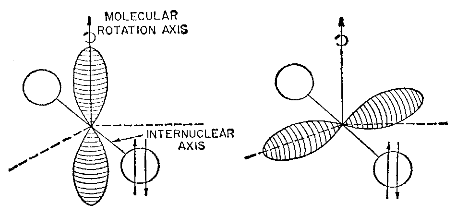

Fig. 1. Schematic representation of the probability distribution of the unpaired electron in OH. In a rotating molecule, the two distributions have slightly different energies and give rise to Λ-doubling. The interaction of the proton magnetic moment with molecular magnetic fields further splits each Λ-doublet into two levels, as shown in Fig. 2.

of the OH molecule, an interaction occurs between the electrons and rotation of the molecule which, in effect, changes each rotational level from a single level to a double level, with a slight energy difference between the two components. This doubling, known as "Λ-doubling," produces energy levels whose separation lies in a portion of the spectrum that is very convenient for present-day radio astronomy. In the case of OH in the ground state, the separation gives rise to a line at 18-centimeter wavelength.

The origin of the OH energy levels is represented in Fig. 1. Since OH has nine orbital electrons, it will have one electron not paired with another, and its spatial distribution may be represented schematically by the two distributions shown in Fig. 1. If the molecule is not rotating, the two configurations will have the same energy. However, in a rotating molecule small forces come into play which give the distributions slightly different energies. This produces Λ-doubling and splits a particular rotational energy level into two, as shown in Fig. 2. If this were the only effect that had to be considered, the OH ground-state spectrum would consist of a single line at 1666 Mc/sec. This would undoubtedly make life easier, but less interesting, for the radio astronomer.

There is another interaction yielding hyperfine structure which must be considered. The nucleus of the hydrogen atom in OH, the proton, has a magnetic moment which interacts with small internal molecular magnetic fields. Different energies result from different orientations of the magnetic moment relative to the internal magnetic field. Since two orientations of the magnetic moment are possible, each level is further split into two levels, as shown in Fig. 2. Also shown in Fig. 2 are the transitions which can occur between the levels; the resulting spectrum is shown in Fig. 3. It is clear why the OH spectrum consists of four closely spaced spectral lines at frequencies of approximately 1612, 1665, 1667, and 1720 Mc/sec.

I have attempted to briefly illustrate the origin of the radio transitions in OH in its lowest level. Nothing has been said about the intensities of the transitions, however. This is a problem requiring a quantum mechanical computation of the transition probabilities for the various lines; the results show that the lines at 1612, 1665, 1667, and 1720 Mc/sec have transition probabilities in the ratios 1:5:9:1, as shown in Fig. 3. An OH medium in thermodynamic equilibrium should exhibit emission or absorption lines with intensities in these ratios, provided the medium is not strongly absorbing. If the medium is strongly absorbing, the line-intensity ratios should approach unity. The failure of observations of interstellar OH to conform to these theoretical intensity ratios was the first anomaly to be discovered (*6*), and practically every subsequent observation has revealed severe departures from the expected ratios.

There is a fundamental difference in character between the OH and the H transitions, which shows itself in the computation of the transition probabilities, and this difference is of great importance in considering the interaction of the OH molecules with the interstellar radiation fields. The OH transitions arise from a redistribution of *electric charge* within the molecule, as depicted in Fig. 1, whereas the 21-centimeter H transition arises from a redistribution of the *magnetic moment* of the atom. Now, electromagnetic theory states that electric interactions in atoms and molecules with an incident radio wave are stronger than magnetic interactions by a factor of the order of v/c, where v is the velocity of atomic or molecular electrons and c is the velocity of light. Typically, v/c is of the order of 10^2, therefore one can expect an electric dipole moment to be of the order of 10^2 times as strong as a magnetic dipole moment. Finally, the intensity of a transition depends on the *square* of the dipole moment, either electric or magnetic, so that one can expect that the OH transitions will be 10^4 times as intense as the H transitions, all other things being equal. This is an important consideration for it implies that OH molecules could be 10^{-4} as abundant as H atoms and still give the same detectable signal in the radio spectrum. Since OH is thought to be of the order of 10^{-7} as plentiful as H in the interstellar medium, it is obvious that a search for OH would never have been considered were it not for this fundamental difference in the character of the two transitions.

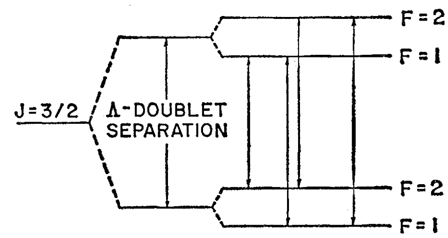

Fig. 2. Energy-level diagram for OH, showing the electric dipole transitions allowed between the levels.

Observations of Radio Absorption

The Soviet astrophysicist Shklovskii was the first to call attention to OH as a potential candidate for study by radio techniques (*7*), and the initial, unsuccessful attempt to detect OH in the interstellar medium by virtue of its radio lines was made in 1956 (*2*). The method used was essentially the same as that used during the successful attempt in 1963, but the frequencies of the lines had not been accurately determined in the laboratory and, therefore, a rather wide region of the spectrum had to be searched. The weak signal expected and the lower sensitivity of the equipment then available made this a difficult problem. However, in 1959 two of the specific frequencies were measured in the laboratory (*8*), and another search be-

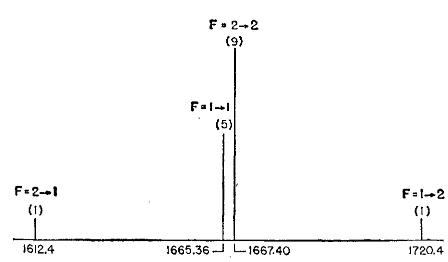

Fig. 3. Spectrum of the transitions shown in Fig. 2. The integers above each line denote the relative strengths of the transition probabilities.

came feasible immediately. This is clearly borne out by the fact that the OH lines were detected during the first night's observations of the 1963 attempt (*1*).

The method used was to direct a radio telescope toward a strong radio source, such as Cassiopeia A, and to "scan" the frequency of the receiver across the expected frequency of one of the OH lines. If OH is present between the observer and the radio source in sufficient abundance, a detectable decrease in the received radio power will occur at the resonant frequency. Such a record is shown in Fig. 4; the sharp dip represents the OH absorption. Also shown in Fig. 4 is the record obtained when the radio telescope is directed adjacent to the radio source and the receiver frequency is varied through the same portion of the spectrum. The latter record is important not only as an aid in the interpretation of the former record but also as a guard against spurious instrumental responses which might produce artificial indications of absorption.

The interpretation of the Cassiopeia A absorption results required simplifying assumptions about the temperature of the OH molecules, assumptions that would not have been necessary had OH emission been detected adjacent to the Cassiopeia radio source. Nevertheless, the observed absorption was indicative of some 10^{14} molecules of OH per square centimeter between the observer and the source. Similar experiments on the 21-centimeter line of atomic H have shown that there are 10^{21} atoms per square centimeter along the same path; thus the OH/H abundance ratio in the interstellar medium is approximately 10^{-7}. As this was the first detection of OH in the interstellar medium, by any method, the inferred OH/H abundance ratio could be compared only with previous theoretical estimates or with inferred abundance ratios of other molecules observed by optical techniques. The previous estimates ranged from 10^{-6} to 10^{-8}; the deduced OH/H abundance ratio fit nicely into this range.

In the initial observations of OH, only the lines at 1665 and 1667 Mc/sec were detected; their intensities were found to be in the ratio 5 : 9, as expected for a weakly absorbing medium. However, when the absorption line of Fig. 4 was examined at higher frequency resolution it was found to consist of two lines closely spaced in frequency, as shown in Fig. 5. This can be readily interpreted as resulting from the presence of two clouds of OH along the line of sight, moving with almost, but not exactly, the same radial velocity. The fact that the radial velocities of the clouds are slightly different gives rise to a Doppler shift, so that the two clouds absorb at slightly different frequencies. Observations at the 21-centimeter line of H had failed to reveal a distinct splitting because the H atom is lighter and, therefore, has a greater line width due to thermal broadening. The greater line width resulted in the absorption from the two clouds being blended into one line, although a slightly asymmetric line. Interpretations of both the OH and H absorption profiles led to a determination of the turbulent velocities and kinetic temperatures within the clouds. The temperatures were found to be 90° and 120°K, respectively, and the turbulent velocities approximately 0.25 kilometer per second (*9*).

One of the many unexpected results in the observations of OH turned up when the absorption spectrum of Cassiopeia A was examined at the frequencies of the two satellite lines, 1612 and 1720 Mc/sec (*10*). Whereas both the 1665- and 1667-Mc/sec transitions show splitting into two lines, neither the 1612- nor the 1720-Mc/sec transition shows any splitting. Furthermore, the absorption at 1612 Mc/sec is approximately one-half that at 1665 Mc/sec, instead of one-fifth, as expected. Finally, the observations indicate a small amount of OH emission at 1720 Mc/sec, but none is detectable at 1612 Mc/sec. These results are shown in Fig. 5. The unusual absorption features and the presence of weak emission have been independently confirmed (*11*). It is very difficult to see how any of these observations can be explained in terms of a medium in thermodynamic equilibrium, and these observations are among the many that are still unexplained.

Other absorption anomalies have been found in the spectrum of the galactic center (*12*). For example, the observed ratios of line intensities among the four lines are 1:2.2:2.7:1, whereas the values expected on the basis of thermal equilibrium are 1:5:9:1. It is tempting to try to explain the observed values in terms of a medium exhibiting large attenuation, for which all ratios would approach unity, but this attempt fails. For example, isolated regions near the galactic center show stronger absorption at 1665 than at 1667 Mc/sec, and many regions show unequal absorption at 1612 and at 1720 Mc/sec (*13*). It seems clear that these ob-

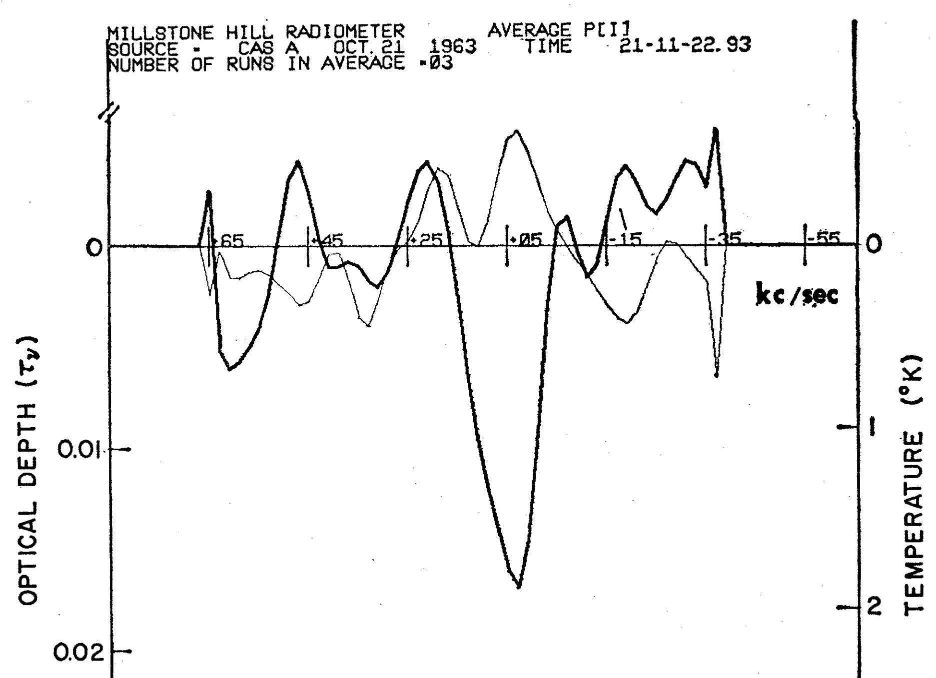

Fig. 4. The initial detection of interstellar OH in the absorption spectrum of Cassiopeia A. The heavy line was obtained with the radio telescope pointed at Cassiopeia A; and the light line was obtained with the telescope directed adjacent to the source (*1*).

servations require the assumption of a nonthermal distribution of the OH molecules among the internal energy states from which the radio lines are derived.

The OH observations in the galactic center pose problems other than anomalous line-intensity ratios. The OH absorption is very strong and extends over a considerable frequency, or velocity, range as compared to H absorption in the same direction (*12, 13*). If the OH profiles for the galactic center are interpreted in a manner similar to that described for Cassiopeia A, then one derives an OH/H abundance ratio of 10^{-4}, some 10^3 times the ratio in the direction of Cassiopeia A. However, this value must be used with extreme caution, because any derived values, based upon the observations, must await a full understanding of the mechanism by which OH is formed, is distributed with respect to its internal energy levels, and absorbs and emits radio energy. From the frequency at which the OH absorption occurs one can determine the radial velocity of the OH relative to the sun, and it is found that the OH is moving *toward* the galactic center with a velocity of 40 kilometers per second. On the other hand, the H which is associated with the galactic center is streaming *away* from the center with a velocity of 50 kilometers per second. This is a curious situation, to say the least, and may force a revision of our ideas about the physical conditions in the galactic nucleus. It should be emphasized, though, that the observations tell us nothing about the distances to the OH and the H; the concept that they are associated with the galactic center rests strictly on interpretations of the accumulated evidence.

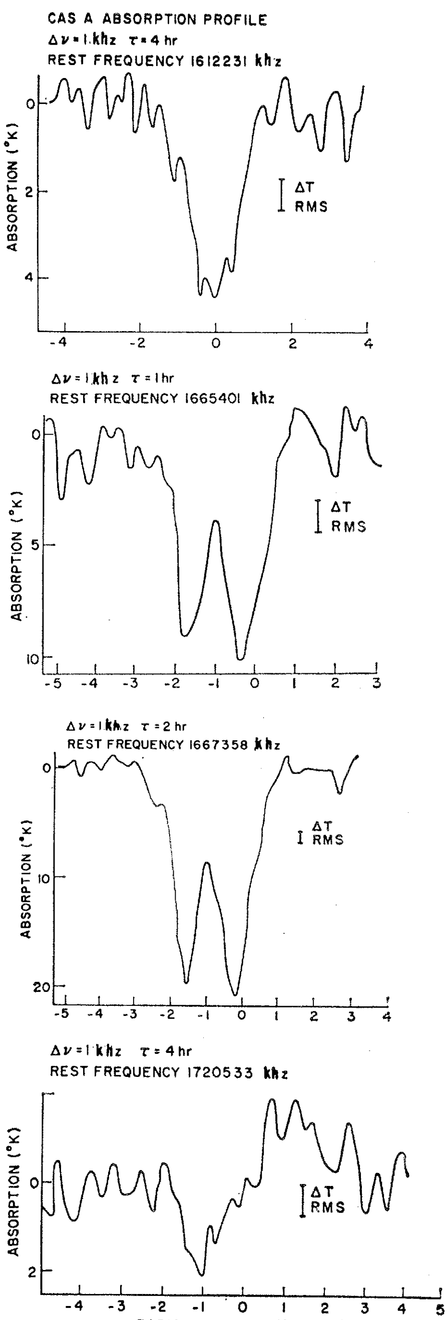

Fig. 5. The total absorption spectra of Cassiopeia A at all four OH frequencies. Note that the two strong lines appear as doublets but the satellite lines are single (*10*). The frequency scale (horizontal axis) is converted to radial velocity by means of the Doppler formula.

The strong OH absorption found in the direction of the galactic center has made another experiment feasible. All the results discussed above have referred to the abundant isotopic species $O^{16}H$, but the observation of strong absorption suggested the possibility that the isotopic species $O^{18}H$ could be detected. The frequencies of the $O^{18}H$ lines are shifted relative to those of the $O^{16}H$ lines because of mass-dependent effects on the molecular energy levels. Though the $O^{18}H$ frequencies have not been measured in the laboratory, they have been calculated to sufficient accuracy, and their importance to radio astronomy has been pointed out (*14*). The terrestrial isotopic abundance ratio O^{18}/O^{16} is 1/490, and if this ratio also applies to interstellar OH, an assumption whose validity is by no means certain, then the lines of $O^{18}H$ should be detectable in the spectrum of the galactic center at frequencies some 30 Mc/sec lower than those of the $O^{16}H$ lines. This has indeed proved to be the case. The $O^{18}H$ line at 1639 Mc/sec, corresponding to the $O^{16}H$ line at 1667 Mc/sec, has been detected in the direction of the galactic center (*15*). The intensity is weak, as expected, and 18

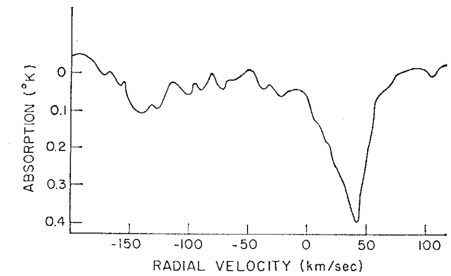

Fig. 6. Record of $O^{18}H$ absorption in the direction of the galactic center. The record was obtained with the 140-foot radio telescope of the National Radio Astronomy Observatory, Green Bank, West Virginia, after 18 hours of integration (*15*). Frequency resolution, 50 kilohertz; rest frequency, 1639.460 megahertz.

hours of integration were required to produce the results shown in Fig. 6. The observations are consistent with an interstellar isotopic abundance ratio of 1/500 for O^{18}/O^{16}, as observed on earth, but the conclusion that the ratios agree must be regarded as extremely tentative at this time. Other $O^{18}H$ lines have not yet been sought, and uncertainties concerning the interpretation of the $O^{16}H$ absorption lines are inherent in any conclusions about the relative amounts of O^{18} and O^{16}. Nevertheless, the observations apparently give the first quantitative information about isotopic abundance ratios in the interstellar medium.

Hydroxyl-radical absorption has been observed in the spectra of many galactic radio sources, and it is found that in many cases the line-intensity ratios depart from the ratios 1:5:9:1 (*11*). It appears that anomalous ratios for OH absorption may be associated with the presence of OH emission. However, the detailed study of OH absorption has been held back, to some extent, by the discovery and study of OH emission having properties far more startling than those of OH absorption.

Hydroxyl-Radical Emission

There are two reasons why it was important to detect OH emission after OH had been discovered in the interstellar medium. First, a proper interpretation of the OH absorption observations in terms of the integrated number of OH molecules requires a knowledge of the excitation temperature of the OH, a quantity that cannot be obtained from absorption measurements alone; second, detailed studies of galactic OH would be sorely limited if

OH could be observed only in the direction of radio sources. Early attempts to detect OH emission were confined to observations at 1667 Mc/sec because it was thought this would be the strongest transition, but all attempts gave negative results (*1, 5, 12, 16*). When OH was finally discovered in emission at 1665 Mc/sec, not 1667 Mc/sec, its properties were so unusual that two out of the first three groups of radio astronomers to observe it did not attribute the line to OH!

Australian observers first observed OH emission in June 1964, when a narrow, intense emission line was detected to the side of an absorption line at 1665 Mc/sec in the direction of the galactic center (*13*). However, the effect was apparently thought to be an instrumental effect and was not reported at the time. Six months or more later, OH emission was observed by groups at Harvard (*17*) and Berkeley (*18*), with properties so unexpected that the Berkeley radio astronomers thought they had detected an unidentified microwave spectral line; they nicknamed the line "mysterium" until identification could be established. Although mysterium has now been identified as OH, the name can hardly be called a misnomer in view of the strange properties exhibited by interstellar OH.

From the beginning, OH emission has been characterized by intense, narrow emission lines at 1665 Mc/sec, with lines of lesser intensity at the other three OH frequencies. Departures by several orders of magnitude from the expected intensity ratios have been noted. Furthermore, the spectrum obtained at one frequency seems to be completely uncorrelated with that obtained at another. This is an extremely difficult phenomenon to incorporate in a theoretical model which attempts to explain the observations.

Another curious fact about the OH emission is its location within the galaxy. It is by no means widely distributed throughout the Milky Way, as is the 21-centimeter emission of atomic hydrogen, but is found only in isolated positions near "HII regions." An HII region is that region about a hot star where the hydrogen is almost completely ionized—hence the name. Such regions are closely confined to the galactic equator and are relatively strong radio sources in the continuum wavelengths—that is, the radio emission of HII regions is not confined to a small spectral domain, as OH emission is. It is estimated that approximately one-third of the galactic HII regions have OH emission associated with them, but this estimate is based on a relatively small sample of about 40 HII regions. No correlation has yet been found between the OH-emitting property and any other property of the HII regions.

Immediately after intense, narrow-band OH emission was discovered it was found that the radiation had strong linear polarization (*19*). This suggested that the radiating system had a preferred direction associated with it, such as a magnetic field or the direction of incident radiation, for example. The detection of linear polarization also suggested that a search for circular polarization of the received radiation be made, and such polarization was detected forthwith (*20, 21*), with polarization approaching 100 percent! The most obvious interpretation of these observations was the conclusion that the lines were split by the Zeeman interaction of a magnetic field with the magnetic moment of OH, and such an interpretation, based on observations at 1665 Mc/sec only, was made (*20*). However, observations at all four OH frequencies rule out a simple Zeeman interpretation because of the lack of correlation between the spectrum at one frequency relative to that at another (*21*).

An example of the observed spectra from the HII region designated W3, one of the most extensively studied OH-emitting regions, is shown in Fig. 7. This figure illustrates many of the interesting properties of OH emission. First, note that signal intensities at 1665 Mc/sec correspond to antenna temperatures of 150°K, whereas the line intensities at 1667 Mc/sec correspond to antenna temperatures that do not exceed 12°K. This is an extreme example of the anomalous intensity ratios mentioned so often above. Note, also, that there is no similarity between the spectra at different frequencies. The circular-polarization characteristics of the radiation are evident in Fig. 7. The solid-line spectra were received with an antenna responsive to right-hand circularly polarized radiation, whereas the dashed-line spectra correspond to left-hand circular polarization. It may be clearly seen that some lines are exclusively polarized in one sense only, within the noise limitations of the observations. Finally, another point is illustrated in Fig. 7. The narrow line at radial velocity of –43 kilometer per second in the 1667-Mc/sec spectrum is only 600 cycles per second wide. This is the narrowest spectral line yet observed in radio astronomy and would correspond to a kinetic temperature of only 5°K if the line width were interpreted as thermal broadening. However, the intensities of the lines preclude this simple interpretation of the line width.

Detailed observations of the OH emission from region W3 have led to determination of all the Stokes parameters specifying completely the polarization properties of the radiation (*22*). Circular polarization has been observed in many other OH-emitting regions (*23*), and it now seems to be established as a general property that OH emission is strongly polarized and OH absorption is unpolarized.

The unexpectedly strong intensity of

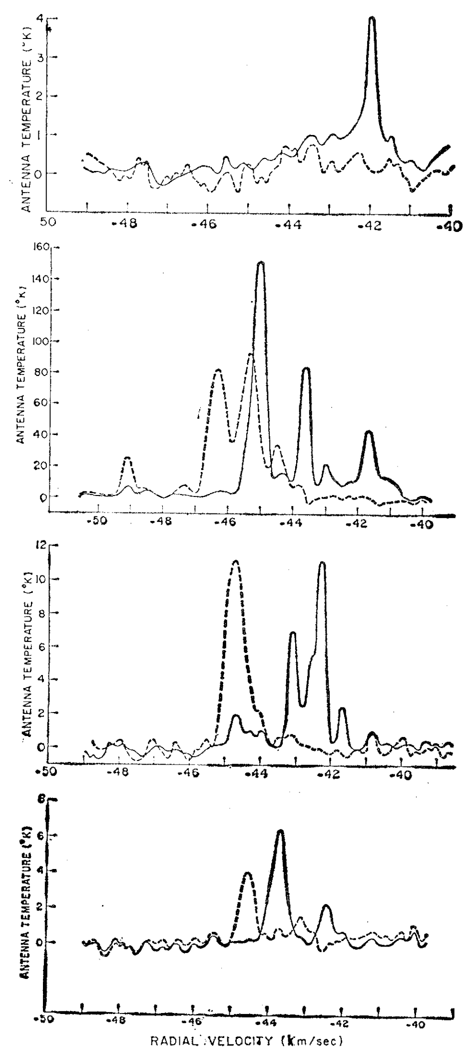

Fig. 7. Four OH emission spectra from the radio source W3: (from top to bottom) spectra at 1612, 1665, 1667, and 1720 Mc/sec. Note that the 1665-Mc/sec lines are stronger than the 1667-Mc/sec lines by a factor of more than 10. The solid line gives the spectrum in right-circular polarization; the dashed line, in left-circular polarization. The lack of correlation between the spectra is well illustrated (*21*).

the OH emission lines has posed several problems. For example, the strongest emission feature in the direction of the galactic center was found to correspond to an antenna temperature of 91°K when observed with a radio telescope whose beam width was 18 minutes of arc (*21*). However, previous observations had shown that the OH-emitting region was less than 5 minutes of arc in angular size (*13*). From these two facts one deduces that the received power, corresponding to temperature of 91°K, must be very much "diluted" by the large beam width of the radio telescope. Therefore, the intrinsic radiation temperature of the emitting source, called the brightness temperature, must be appreciably greater. For the source in the direction of the galactic center, the brightness temperature must exceed 1300°K. If the same upper limit on angular size is assumed for the W3 source, the corresponding value is 2000°K (*21*). These temperatures may be contrasted with a maximum of 100°K or so observed for galactic H radiation at the 21-centimeter line. Two problems presented themselves: (i) What mechanism was exciting the OH to at least 2000°K? (ii) What was the angular size of the OH-emitting regions?

To answer the second question, observers at California Institute of Technology and M.I.T. undertook interferometric observations (*24, 25*). The observations could not provide an answer but did establish the fact that the angular size was at least as small as 20 seconds of arc. For the region-W3 source, this implies a brightness temperature in excess of 2×10^6 degrees Kelvin. Several OH sources were examined, with similar results, although some of the sources, previously thought to be single, were revealed to be double, or even more complex (*25*). But the question remained, What was the angular size of the OH-emitting regions?

According to first principles of interferometry, in order to determine smaller and smaller angular sizes one must use more and more widely spaced antennas. Since the object now was to determine angular sizes of less than 20 seconds of arc, the problem had outgrown the province of any one observatory. Two groups of two observatories each started independent observations, still seeking an answer to the question of angular size. In Cambridge, Massachusetts, M.I.T. and Harvard combined antennas, with a separation of 74,000 wavelengths (13 kilometers) (*26*), and in England groups at Jodrell Bank and Malvern joined forces, with an antenna spacing of 700,000 wavelengths (127 kilometers) (*27*). Both groups studied the strongly OH-emitting region W3, and the Jodrell Bank-Malvern group studied three additional sources. By virtue of the fact that their antenna spacing was ten times greater, the English observatories could provide better information about angular size than the Massachusetts group, but still the observations failed to provide a definite size. The emitting sources were shown to have an angular size of less than 0.1 second of arc in most cases. The most intense feature in the W3 source, the 1665-Mc/sec line at −45 kilometers per second in Fig. 7, was found to originate from a region whose apparent angular size is less than 0.05 second of arc. This is an astonishing result. The distance to region W3 is estimated to be approximately 1700 parsecs, therefore the apparent linear dimension of the OH-emitting region is only 4×10^{-4} parsec, or 85 astronomical units. When this value is compared with the diameter of the orbit of Pluto, which is 80 astronomical units, one sees that the apparent size of this particular region is at least as small as our solar system! Furthermore, its intrinsic radiation temperature, or brightness temperature, must exceed 10^{11} degrees Kelvin. When this value is contrasted with the central temperatures of stars, typically 10^7 to 10^8 degrees Kelvin, it may be seen that caution must be exercised in thinking of the 10^{11} degrees Kelvin as a physical temperature in the usual sense.

The wide-baseline interferometry revealed other information besides that related to angular size. Both the U.S. and the English groups found that the various features of the 1665-Mc/sec spectrum from region W3, shown in Fig. 7, originated from separate regions of space. In other words, the W3 source of OH radiation, originally thought to be a single source of angular size less than 20 seconds of arc, was found to consist of at least four individual sources, separated from each other by 1 or 2 seconds of arc, each radiating at its own frequency and emitting radiation of characteristic polarization. Although the complete results of both series of observations are not yet available, it is clear that the two groups are in essential agreement on the multiplicity of sources (*26, 27*). The English workers have detected a similar effect in at least one other OH source (*27*).

One further result of observations of galactic OH emission remains to be mentioned. Radio astronomers at Berkeley have reported that the amplitudes of OH emission lines from several sources vary with time, on time scales of a few days or weeks (*28*). These observations are difficult to check since there seems to be no predictable order to the variations. Other observers have failed to confirm the observation of time variations; one instance of possible confirmation has been reported, but the variation was only slightly larger than the limitation set by receiver noise (*23*). Source W3 has been extensively studied, and all observers agree that the OH radiation from this source is not time-varying. Until the reported time variations can be confirmed, it is premature to speculate on the implications.

All the observational results presented to date have originated in our own galactic system. One naturally asks, Can we detect OH radiation from other galactic systems? The answer at this time is no, but not because attempts have not been made. A preliminary search for OH emission from HII regions in the Large Magellanic Cloud was made by Australian observers, who tentatively concluded that OH emission comparable to that from galactic source W3 was not present (*29*). A similar survey of eight galaxies, for which data at wavelength of 21 centimeters are available, was conducted in an effort to detect OH emission at 1665 Mc/sec, but without success. The upper limits on the OH/H ratios, derived from the observations, range from 7×10^{-5} to 2×10^{-6} (*30*), as compared with an abundance ratio of 10^{-7} in our galaxy.

Possible Maser Mechanisms

Most attempts to explain the OH observational results have centered around some kind of population inversion of the energy levels, whereby the OH medium would be converted into a medium which amplifies rather than absorbs. This is a common laboratory phenomenon which has led to the development of maser and laser devices, but I am unaware of any previously known instance of the process occurring in nature. For amplification to occur, the population of the higher-energy levels—of those defining the radio lines—must exceed that of the lower-energy levels, so that the net effect of a radio wave's passing through the OH is to induce more transitions from high to low energy levels than from low to high levels. Since transitions from high to low energy levels add energy to the radio wave, and those from low to high levels subtract energy, a medium with population inversion will add energy to the radio wave—that is, will amplify the radio wave.

The most obvious reason for attempting to invoke maser action to explain the OH observations is to meet the requirement for explaining the extremely intense lines. As discussed above, the intrinsic temperatures of the lines correspond to temperatures in the range 10 to 100 billion degrees Kelvin, a circumstance which is highly suggestive of amplification processes because such temperatures exceed, by several orders of magnitude, known physical temperatures. But the intensity of the lines is not the only reason for suspecting maser processes. Extremely narrow lines have been observed, and amplifying processes can lead to a line narrowing, line shapes as well as widths being altered by the amplification. Thus, line widths of 600 cycles per second, corresponding to kinetic temperatures of 5°K, could exist in situations where the line intensities correspond to temperatures between 10^{10} and 10^{11} degrees Kelvin. Furthermore, if the maser mechanism were sensitive to polarization, then the observed radiation might exhibit a large degree of polarization, such as is observed.

Finally, another property of maser processes should not be overlooked. If an OH medium can be brought to a state of amplification, then sources of radiation lying behind it, as viewed from the earth, or emissions of the medium itself, will appear as sources of extremely small angular size. This will be true because of the coherent nature of the amplifying processes, which produces a high degree of directionality in the amplified radiation. If this is indeed happening, then the small angular sizes observed in the interferometric observations may actually be "apparent" sizes rather than true angular sizes. For this reason, the linear dimensions of the OH-emitting regions may be considerably larger than those inferred from the observations.

For amplification to occur, the thermal distribution of molecules among their internal energy states must be disturbed to the extent that the population is inverted. Many mechanisms have been invoked for accomplishing this in the laboratory; most commonly, radiation at some higher frequency is used to upset the equilibrium population of molecules. This radiation is often referred to as the "pump," because its net effect is to pump molecules from the lower energy state to the upper state so that amplification may occur. Various pumping mechanisms have been invoked in attempts to devise a hypothetical celestial OH maser to explain the observations. Suggested schemes for radiation pumping include use of ultraviolet (*31*), infrared (*32*), and radio (*33*) radiations as a means of inverting the molecular populations, and a mechanism involving collision of electrons or ions with OH molecules has been considered (*34*). Some of these proposals have not been investigated in a quantitative manner (*32*), or have been shown to give inversion for only one, or two, of the transitions (*33, 34*), and none can be said to be in agreement with all the observational results. The recent observation that the different components of the 1665-Mc/sec spectrum from the W3 source originate in spatially separated regions (*26, 27*) has not yet been incorporated in the maser theories, but the result obviously imposes further constraints on the theories. It will be interesting to see whether the 1667-Mc/sec components correlate spatially with any of the 1665-Mc/sec components, but the weakness of the lines at 1667 Mc/sec make the observations more difficult.

Maser amplification might provide a mechanism for generation of the high degree of circular polarization observed (*35*). Under conditions of maser saturation it is possible to produce predominantly circular polarization without having large magnetic fields, and such effects have been observed in the laboratory. No detailed treatment of this problem with specific reference to the cosmic-OH observations has been carried out.

The extreme conditions and the theoretical complexity demanded by the OH observational results make it very clear that a simple theory is not likely to account for the varied phenomena that have been discovered. Possibly various maser theories can be combined to provide a satisfactory explanation, but the theoretical analyses have not yet been carried that far. In any event, the complexity of the problem is such that no theory will gain immediate acceptance, and, indeed, one cannot expect a successful explanation of the observations until the flow of basic observational results begins to abate. If this time has arrived, it has only recently done so.

Interstellar Communications

Perhaps it has occurred to some readers that the radiation from the interstellar medium, attributed here to OH molecules, may be a precursor of interstellar communications. It is a fascinating thought, and one that has not escaped the scientists involved in OH research, although few would care to admit this publicly, perhaps. Such speculations have passed well beyond the domain of science fiction in our times. Many outstanding scientists have thought about the question and have published their conclusions (*36*), and one attempt has been made to detect interstellar signals indicative of an intelligent source (*37*). A few comments on this subject may not be entirely out of order.

Prior to 1963, when the OH lines were discovered, practically all speculations on interstellar communications began with the logical assumption that frequencies very near the 1420-Mc/sec line of atomic hydrogen, or some multiple or submultiple thereof, were those which would be used for such purposes. After all, the 1420-Mc/sec line was, and is, a unique frequency, universally known, and located in an accessible portion of the radio spectrum (*36*). But the hydrogen line is not quite as unique as it was before 1963. Many other radio lines are known now, only one set of which have been covered in this article, but one can build a good case for considering frequencies near the OH lines to be likely candidates for interstellar communications. Since both the OH and H lines are in the same region of the radio spectrum, considerations of atmospheric absorption, galactic continuum noise, and technological developments are common to both, so no distinct advantage can be claimed for one frequency over the other on these grounds. However, it appears that the OH frequencies might be prime candidates for interstellar communications when one considers the following questions. (i) If one civilization wanted to attract the attention of another, which it suspected might be actively engaged in radio astronomy or even actually listening for signals, what better way would there be to attract attention than to violently upset the expected intensity ratios of the four OH lines? One can envision the "receiving" civilization immediately noticing the anomaly, giving it the name "mysterium," subsequently "identifying" it as OH, noting the strong polarization, carrying out interferometric observations with ever-increasing baselines to establish the angular size of the strange emitter, and inventing sophisticated theories to explain the observations. One can *not* envision the receiving civilization simply *ignoring* the observations! (ii) If OH in the interstellar medium is capable of amplification, because of some form of maser inversion, even in small interstellar clouds, then wouldn't the OH frequencies be likely ones to be used for transmission of information over interstellar distances? In the interest of conserving power, improving signal-to-noise ratio, or communicating over increased galactic distances, it seems that use of an amplifying propagation medium would offer some promising results. (iii) Are there, because of the coupling between the OH energy levels, ways in which radio power pumped into an OH cloud at one transition frequency could render the cloud an amplifier, or a very large transmitting antenna, at another OH line frequency? It is a foregone conclusion that the "transmitting" civilization is far more advanced in radio technology and astronomical knowledge than our own, so conceivably it would have found a means—such as focusing, or providing preferential propagation for a specific polarization—to utilize the special properties of interstellar OH to serve its communication purposes.

There is no evidence that the OH radiation is really interstellar signaling, and I am making no such proposal. However, one might conclude that the observations are suggestive, because the OH emissions have many of the properties originally suggested for interstellar signals, and sought in the search for such signals (*36, 37*). These properties are strong intensity, narrow bandwidth, origin from regions of extremely small angular size, strong polarization, and, perhaps, variation with time. But OH radiation has other properties that one would not expect to find associated with interstellar communications—properties such as origin in, or near, HII regions. Since these are regions of high ionization, relatively close to a star of high luminosity in the ultraviolet, one would expect them to be conducive of life (*36*). Furthermore, the apparent time variations of the amplitude of the signals seem to have a period of days, or weeks—somewhat longer than would be expected for interstellar communications, but not so much longer as to be unreasonable (*36*).

Several important clues which would help in distinguishing between naturally and artificially generated signals have not been detected. Such observations would require extreme care and extensive data processing. For example, time variations of all sorts should be sought, not only amplitude variations. A discovery of frequency variations, especially systematic ones, would be extremely important. If the emitter, real or artificial, is rotating or is in orbit about a heavy body, then the frequency of the lines will vary systematically because of the Doppler shift. Statistical properties of the signals are also important. Emissions arising from natural processes should be randomly varying in both amplitude and phase. On the other hand, the detection of any coherence, or nonrandomness, of amplitude and phase may be extremely difficult to explain in terms of natural mechanisms. These are important observations which have not been made.

The speculative character of the foregoing remarks should be clearly borne in mind. Interest in interstellar communication and its detection has grown markedly in recent years, but much of the effort seems to have been devoted to finding how to conduct a search—more specifically, a search centered at frequency of 1420 Mc/sec. Furthermore, it is often assumed that another civilization is attempting to establish contact with us. The possibility of an accidental discovery, which in my opinion is more likely, is rarely considered. If one grants that such things are possible, then perhaps the initial evidence of interstellar communication would be our detection of a vast interstellar communications network, which would someday accept us as its newest member. Is it possible that we are getting close?

Must the Observations Stop?

Before concluding, I should call attention to a situation of man's making which could preclude our ever understanding the OH phenomena, or of deriving any knowledge from the wealth of information that is now buried in the observations. The OH lines lie in a crowded *and unprotected* portion of the radio spectrum. Man's proliferation of electronic devices will soon so crowd the radio spectrum with transmissions that radio astronomy will cease to exist, except for a few portions of the spectrum where international agreements exclude other users. It is difficult to convince a government agency, or a communications company, that a segment of the radio spectrum should be left *totally* unused so that radio astronomers can listen—just listen. Furthermore, the problems are compounded by the fact that it does little good to protect one frequency in one country and another frequency in another country on the opposite side of the globe, particularly in this era of earth-orbiting satellites, space communication, and planetary space probes. Truly international cooperation is required, preceded by a large amount of cooperation and understanding at the national level. Both kinds of cooperation are hard to obtain for such a nonprofit venture as radio astronomy, although recently several decisions favorable to radio astronomy have been made within the United States.

An unusual series of circumstances at the time of the discovery, in 1963, of radio-frequency lines of OH has set the stage for protection of the OH frequencies, but it is only a beginning. The OH lines were detected in October 1963, at the precise time that communications engineers and diplomats were meeting in Geneva, Switzerland, to try to agree on frequency allocations on a worldwide basis. Radio astronomy was only one of many groups competing for their share of the radio spectrum. Agreement was reached to protect the H line at 1420 Mc/sec from interference, but the participants at the meeting could see no strong reason to allot valuable portions of the spectrum to other lines, especially when radio astronomers weren't even sure they could be detected. The mood was such that only a very limited number would even be considered, and who was to say which lines were more important than others? It was in this atmosphere that the radio astronomer with the U.S. delegation received a cable informing him that the OH lines had been detected at M.I.T. The cable reached him on the day before the OH lines were to be given final consideration!

Obviously, last-minute scientific discoveries are not the sort of thing that can be readily incorporated into the deliberations of an international, decision-making conference, but the receipt of the cable was important because it provided considerable support for the radio astronomers' plea that the OH frequencies be protected for future radio-astronomical use. As a result, a footnote was appended to the table of frequency allocations urging that consideration be given to the needs of radio astronomy for protection of the OH lines, and promising that the matter would be given further attention at the next international conference (*38*). Little more than this could be expected on such short notice, but it is obvious that the case for protection of the OH lines must be clearly documented and brought to the attention of the appropriate officials in all countries before the next assembly. It would be wrong to conclude that the OH frequencies are now protected, or that, without further work, they will be at some future international conference.

Summary

The discovery of the radio frequency lines of OH gave the first positive evidence of the existence of OH in the interstellar medium. In the 3½ years that have intervened, many observations have revealed totally unexpected anomalies in the radio-spectral properties of interstellar OH. As a result, no reliable astrophysical information has been derived from the OH observations, but a large body of information is waiting to be unraveled. The interpretations of the data which have been made, such as the values derived for OH/H abundance ratios or for the kinetic temperatures of interstellar gas clouds, must be viewed with caution. They may turn out to be drastically in error, once the origin of the OH emission and absorption is fully understood.

The OH radiation has been found to give extremely strong emission lines, typical of radiation temperatures of 10^{10} to 10^{11} degrees Kelvin, and lines as narrow as 600 cycles, and to originate from regions whose apparent dimensions, in at least one case, are less than those of our solar system. Furthermore, emitted OH radiation is strongly polarized, often as much as 100-percent polarized, while absorbed OH radiation is unpolarized. Strong departures from theoretical line-intensity ratios are noted in both emission and absorption spectra, and variations of the amplitudes of OH emission lines with time have been noted. Finally, different features of a single spectrum—for example, the 1665-Mc/sec spectrum from the radio source W3—arise from small, separated regions of space. Each feature appears to represent a separate source. All this presents a picture for which no satisfactory explanation has been offered, although several schemes involving maser amplification have been proposed. When OH emission was discovered it was given the Latin name "mysterium"; a more appropriate name would be difficult to find.

Note added in proof. Personnel of M.I.T. and the National Radio Astronomy Observatory have recently completed an interferometric experiment in which antennas separated by 845 kilometers were used, in another attempt to determine the angular size of the OH-emitting sources. Independent atomic-clock frequency standards provided timing synchronization. Preliminary results show that the source W3 is still unresolved, and thereby place an upper limit of 0.02 second of arc on its apparent angular size. This value corresponds to a linear dimension of less than 35 parsecs and to brightness temperatures of the order of 10^{12} degrees Kelvin. This work was performed by J. M. Moran, P. C. Crowther, B. F. Burke, A. H. Barrett, A. E. E. Rogers, J. A. Ball, J. C. Carter, and C. C. Bare [*Science*, **157**, 676 (1967)].

Since antenna spacings of ~1000 kilometers are insufficient to resolve the OH sources, transcontinental and transoceanic experiments are required. Joint observations are currently under way involving personnel of M.I.T., the National Radio Astronomy Observatory, the University of California at Berkeley, and Jodrell Bank in England. It is obvious that we are rapidly approaching the limit of antenna spacings set by the size of the earth. Advances beyond that will have to await the adaptation of interferometric techniques to earth-orbiting satellites or establishment of a radio-astronomy observatory on the moon.

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