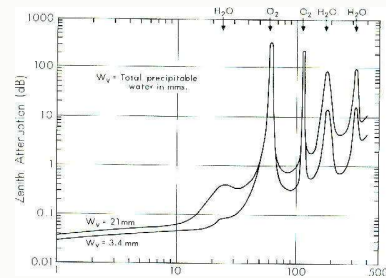


Historical Introduction to Radio Astronomy

Robert L. Brown
National Astronomy and Ionosphere Center

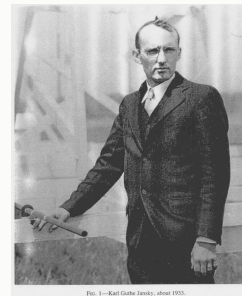
Definitions: "Radio Astronomy"



Chronology of Radio Communication Technology

- 1901 Marconi—First transatlantic Radio Communicator
 - ▶ Frequency < 100 kHz
 - ▶ Limitations: Bandwidth, "atmospherics"
- 1920 "Shortwave"—intercontinental communication
 - ▶ Frequency 1.5 MHz
 - ▶ Technology: Vacuum triode tubes
 - ▶ Limitations: Bandwidth, "atmospherics"
- 1927 AT&T Longwave transatlantic telephony (voice)
 - ▶ Frequency 60 kHz
 - ▶ Enabling Technology: Directional Antenna Design
 - ▶ Limitations: Bandwidth, "atmospherics"
- 1929 AT&T shortwave transatlantic telephony (voice)
 - ▶ Frequency: 9 – 21 MHz
 - ▶ Enabling Technology: Quartz Crystal Oscillator
 - ▶ Limitations: "Atmospherics", RFI, Antenna Directionality
- 1928 Karl Jansky joins AT&T Bell Labs

Karl Jansky The Discovery of Cosmic Radio Emission



Karl Jansky The Discovery of Cosmic Radio Emission

Jansky's Task and Resources at Bell Labs

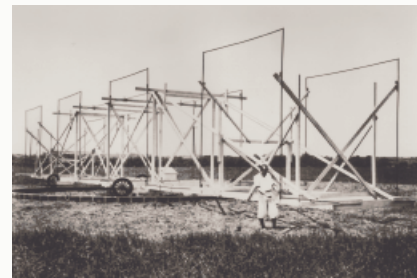
Task: Identify the optimum frequency and technology requirements for shortwave transatlantic communication

Resources:

- ▶ Modified "Bruce Array" of tuned, quarter-wave elements giving good directionality (wavelength 14.6m, frequency 20.5 MHz)
- ▶ Superheterodyne receiver stable enough to integrate for long times (30 sec) with a bandwidth of 26 kHz ($BW/RF \sim 0.1\%$)

Technique: Rotate antenna in azimuth every 20 minutes scanning the sky

[From "The Early Years of Radio Astronomy", ed W. T. Sullivan III]



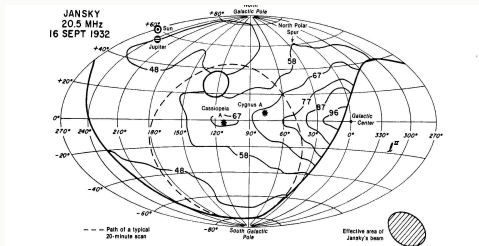


Fig. 1.1. A modern reflection of Jansky's data taken on 16 September 1932 (after Sullivan 1978). The contour map is in galactic coordinates in which 0° latitude corresponds to the plane of the Milky Way and 0° longitude corresponds to the galactic center. Contours are labeled in 100 K.

What Led to Jansky's Achievement?

- ▶ Ability to discriminate directionality (aka good "angular resolution")
- ▶ Large area sky survey
- ▶ Good survey sensitivity (the "best" receiver and detector)
- ▶ Repetition of observations over a long period of time (> 2 years)
- ▶ Conscientious attention to the need to understand subtle effects in the data

Reaction of Astronomers and Engineers to Jansky's Achievement

- ▶ Very limited, virtually ignored
- ▶ Jansky published in the Proc Inst Radio Engineers, not astronomy journals
- ▶ No real way to place in scientific context
- ▶ Observations not understandably quantitative
- ▶ Whipple and Greenstein (1937) speculated the emission came from warm, large (> 1 micron), dust grains

Reaction of the Public to Jansky's Achievement

New York Times, May 5, 1933, Front Page:
 "New radio waves traced to center of the Milky Way...mysterious static reported by K. G. Jansky...recorded and tested for more than a year to identify it as from Earth's Galaxy...its intensity is low, only a sensitive receiver is able to register it"

"No evidence of interstellar signaling"

Grote Reber The Birth of Radio Astronomy



Grote Reber, about 1937.

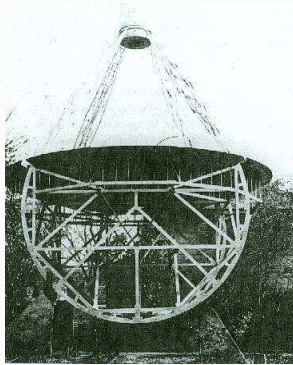
Grote Reber The Birth of Radio Astronomy

- ▶ Professional, and extremely capable, radio engineer working for Collins Radio and living in Wheaton, Illinois.
- ▶ Avid radio amateur who read with keen interest Jansky's 1932 and 1933 papers and saw Jansky's work as a challenging opportunity for radio technology.
- ▶ Also aware of the Whipple and Greenstein interpretation of the origin of cosmic radio waves.
(Proc Institute of Radio Engineers, 1958, vol 46, p15)

Reber's Radio Telescope

Requirements:

- ▶ Telescope should be suitable for observations over a wide range of wavelengths in order to examine the spectrum of cosmic radio emission
- ▶ Good angular resolution is important for associating radio emission with known astronomical features/phenomena
- ▶ Visibility of as much of the sky as possible is important



Reber's Initial Experiments (1938): 3300 MHz (9 cm wavelength)

Choice of wavelength motivated by:

- ▶ Understanding that the intensity of thermal radiation (of dust grains in this case) in the long wavelength, Rayleigh-Jeans, part of the spectrum increased with decreasing wavelength, $I \sim \lambda^{-2}$
- ▶ Availability of the newly introduced RCA 103A magnetron and zinc sulfide crystal detector

Reber's Initial Experiments (1938): 3300 MHz (9 cm wavelength)

Limitations:

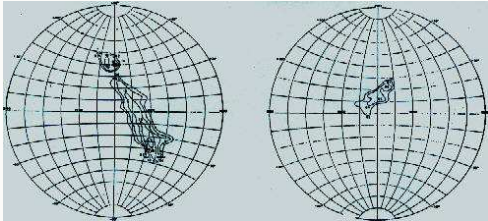
- ▶ Reber was working, independently, at frequencies greatly in excess of the state of the art in radio communications.
- ▶ Instrumentation was unstable, gain variations masked spatial (time) variation of the cosmic radio emission
- ▶ Sensitivity was adequate to detect the radio emission if its intensity $I \sim \lambda^{-2}$ but inadequate otherwise. Thermal emission was excluded.

Second Generation of Experiments (1938/39): 33 cm Wavelength (910 MHz)

Decision to work at a lower frequency where conventional, commercial, triode tubes RCA 953 were available and could be used to significantly increase the sensitivity.

Actual sensitivity not well established. No detections made.

Reber's 480 MHz contour map published in the Proceedings of the Institute of Radio Engineers in 1948. Cygnus A is resolved from Cygnus X. The beamwidth is 4 degrees.



Plans to Search for the Hydrogen 21-cm Spectral Line

- ▶ In 1945 Reber met with H. C. van de Hulst who encouraged Reber to search for the HI 21-cm spectral line. Van de Hulst could not reliably estimate the strength of the line, or even if the line would appear in absorption or emission.
- ▶ Reber accepted the challenge and built a 1200-1600 MHz signal generator and a bench-top 1420 MHz amplifier.
- ▶ The work was never completed. Reber left Wheaton, Illinois in 1947.

Reaction of Astronomers and Engineers to Reber's Achievements

1. Reber did publish, initially, in the astronomical literature (ApJ).
2. His papers received an unusual refereeing process that included a "site visit" by the ApJ editor and others.
3. The astrophysical implications of his work were not immediately appreciated.
4. The field blossomed with the entry into the field of radar engineers experienced from WWII.

What Led to Reber's Achievements?

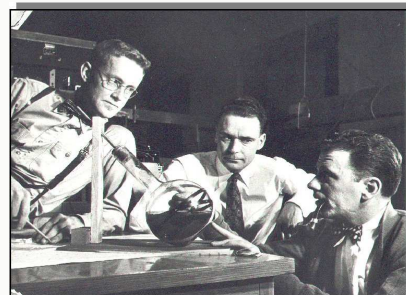
- ▶ Ability to discriminate directionality (aka good "angular resolution")
- ▶ Large area sky survey
- ▶ Good survey sensitivity obtained using wide bandwidths for RF reception
- ▶ Fast sampling to exclude local RFI
- ▶ Enthusiasm to employ cutting-edge technology to radio astronomical research
- ▶ Conscientious attention to the need to understand instrumental effects and calibration
- ▶ Persistence

Reber Telescope in Green Bank, WV



Harold Ewen and Ed Purcell

The Discovery of the 21-cm Spectral Line of Atomic Hydrogen



Harold Ewen and Ed Purcell

The Discovery of the 21-cm Spectral Line of Atomic Hydrogen

Background:

In 1945 van de Hulst calculated the frequency of the hyperfine structure line of neutral atomic hydrogen and suggested that this line, at 1420 MHz, would be a useful astrophysical probe of interstellar gas. However, he was skeptical it could be detected because the A-value of the transition was so small.

Ewen was working on RF sources around 1.5 GHz for the Harvard cyclotron

Purcell, a Harvard physicist, approached Ewen with the idea that they build a simple receiver and horn antenna to see if the van de Hulst line was detectable. This was meant as a modest effort with no high expectations for its success.

The Instrumentation

- ▶ Receiver: Ewen built a simple mixer receiver in his spare time. He consulted with Bob Pound on the mixer and LO design (Pound was responsible for much of the development work on "high" frequency sources). The receiver employed the first use of frequency switching as a means to establish a reference.
- ▶ Telescope: Ewen designed and built a simple horn antenna. A horn was used because Ewen could calculate its gain accurately and hence provide a limit to the HI line strength that was appropriately calibrated in physical units.

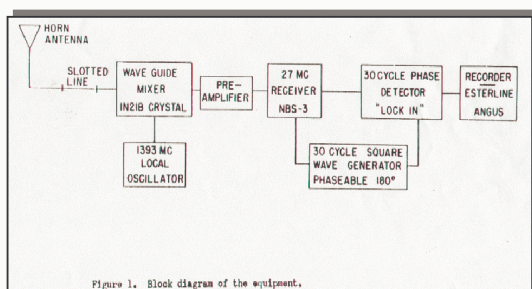


Figure 1. Block diagram of the equipment.

Hydrogen Line Receiver Schematic -- from doctorate thesis



The Effort

Doing the work in spare time on weekends, Ewen estimated that their total effort was no more than 3-4 months of work.

The initiative was funded by a \$500 grant from the American Academy of Arts and Sciences

The HI spectral line was detected nearly immediately with the horn antenna protruding from the Lyman Laboratory at Harvard.



Competitors

The Dutch group led by Jan Oort, and including van de Hulst, had been seeking to detect the HI line but had been delayed by a fire in their laboratory. Hearing of the Ewen and Purcell result, they too adopted frequency switching and found the line.

Frank Kerr, visiting at Harvard at the time, encouraged Joe Pawsey at CSIRO to implement a frequency switching receiver and search for the line.

Jan Oort and Henk van de Hulst



2. In discussion with H.C. van de Hulst at the reception on the occasion of Oort's 50th birthday at a staff member of Leiden Observatory, 1964.



Publications

The American and Dutch results were published in 1951 in the same issue of Nature.

Ewen and Purcell, Nature v.168, p. 356

Muller and Oort, Nature v.168, p. 357

That issue of Nature included a report that the Australian group had confirmed the detections.

What Led to the Ewen and Purcell Achievement?

1. Purcell's interest in atomic spectroscopy. He was aware of van de Hulst's calculations and understood its potential astrophysical importance.
2. "Doc" Ewen's work and expertise on RF devices at microwave frequencies that could be leveraged to build the equipment. Ewen was fascinated by the challenge.
3. A new observing technique, frequency switching, that proved to be necessary to detect the very extended HI emission. Purcell recognized that HI would be ubiquitous, and Ewen/Pound designed and implemented a radiometer and LO to meet the need.

"Doc" Ewen (1951)



Jocelyn Bell Burnell The Discovery of Pulsars



Jocelyn Bell Burnell The Discovery of Pulsars

Tony Hewish at Cambridge (England) sought to identify Quasars from radio galaxies by means of interplanetary scintillation. Quasars, being of small angular size scintillate in the interplanetary medium, the large radio galaxies do not.

Hewish designed an aerial array to operate at 81.5 MHz for the scintillation observations.

Jocelyn Bell, and other thesis students, built the array in 1965-66.

(From Serendipitous Discoveries in Radio Astronomy, ed K. Kellermann and B. Sheets)

The Cambridge Scintillation Radio Telescope

Scintillation is characterized by rapid variability, twinkling, of compact radio sources.

The physical cause of scintillation is the passage of "blobs" of interplanetary plasma through the line of sight between the radio source and the Earth. Because the local structure of the interplanetary plasma is time-dependent not every small radio source scintillates every day. Repeated observations are required.

Fast data sampling was needed, at ~ 0.1 sec, to see scintillation

To achieve sufficient sensitivity with short integrations the telescope area must be large.

The Cambridge scintillation radio telescope had an effective area of 4.5 acres.

Data Taking and Processing at the Cambridge Scintillation Radio Telescope

The radio telescope formed 4 simultaneous beams that scanned 4 different declinations each day.

In 4 days all declinations between -10 deg and $+50$ degrees were covered. The observations were repeated. Each patch of sky was observed 30 times in 6 months.

Although interplanetary scintillation is a phenomenon seen in the ecliptic, and hence is prominent during daytimes, data were taken 24 hours/day

The data were recorded only on strip chart recorders, ~ 100 feet of chart paper per day, every day, all analyzed by Jocelyn Bell by hand.

Types of Sources Identified

1. Non-scintillating continuum sources
2. Sources that scintillate weakly to very strongly
3. RFI—automobile ignition, aircraft, transmitter harmonics
4. Rapidly variable "scruff" that appeared neither with the time signature of RFI nor with that of a scintillating source. This was seen in $\sim 1/4$ of an inch of the 100 feet of chart paper recorded daily. The variations were periodic to high precision.

Examples of scintillating sources. The source on the left is weak and shows no scintillation; the source in the center is strong and scintillates strongly; the source on the right scintillates moderately.

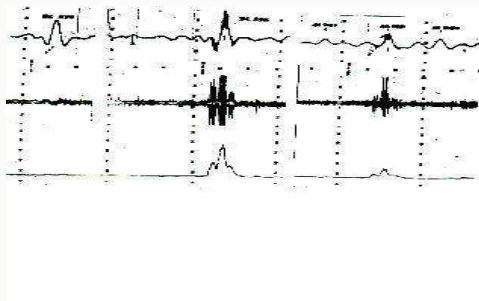
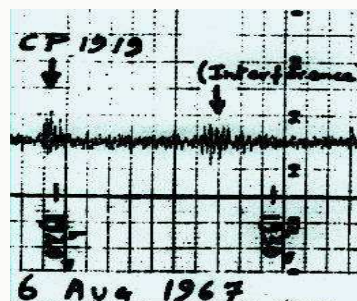
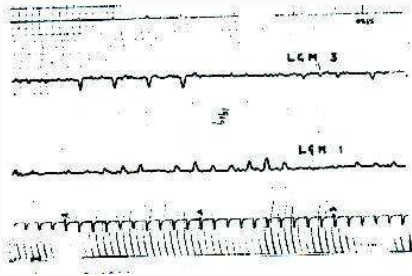


Chart recording of the pulsar detection and an interference signal somewhat later in time



Fast chart recording of pulsar emission (LGM nomenclature is "Little Green Men")



Steps to the Conclusion that the "Scruff" had a Cosmic Origin

1. The scruff, when present, always appeared in the same declination strip and never in other declination strips observed at the same time.
2. Continuous observations over the interval of more than 6 months lead to the conclusion that the scruff was fixed in right ascension, not local time.
3. Observations with another telescope also operating at 81.5 MHz gave the same result.
4. Another example of "scruff" with the same characteristics were found in the data set (the archive of chart recordings).

Observation of a Rapidly Pulsating Radio Source

by
A. HEWISH
S. J. BELL
J. D. H. PARKINGTON
P. F. SCOTT
R. A. COLLINS
Mullard Radio Astronomy Observatory,
Cambridge University.

In July 1967, a large radio telescope operating at a frequency of 81.5 MHz was brought into use at the Mullard Radio Astronomy Observatory. This instrument was designed to investigate the angular structure of compact radio sources by observing the nulls formed by the irregular structure of the interplanetary medium. The initial survey includes the whole sky in the declination range $+68^{\circ}$ to -84° and this area is scanned once a week. A large fraction of the sky is thus under regular surveillance. Soon after the instrument was brought into operation it was noticed that signals which appeared as if to be weak periodic interference were repeatedly observed at a fixed declination and right ascension; this result showed that the source could not be terrestrial in origin.

Systematic investigations were started in November and high speed records showed that the signals, when present, consisted of a series of pulses each lasting ≈ 0.2 s and with a repetition period of about 1.337 s which was now found to be associated with extreme accuracy.

Further observations have shown that the time period is constant to better than 1 part in 10^6 although there is a systematic variation which can be ascribed to the orbital motion of the Earth. The repetitive nature of the recorded signals is opposed by the periodic passage of a signal of decreasing frequency through the 1 MHz pass band of the receiver.

The remarkable nature of these signals at first suggested an origin in terms of man-made transmissions which might also have been quite possible, possibly due to the reflection of terrestrial signals from the Moon. None of these interpretations can, however, be accepted because the absence of any parallels above that the source lies far outside the solar system. A preliminary search for further pulsating sources has already revealed the existence

of three others having remarkably similar properties which suggests that this type of source may be relatively common at a low flux density. A tentative explanation of these unusual sources in terms of the stable oscillations of white dwarfs or neutron stars is proposed.

Position and Flux Density

The aerial consists of a rectangular array containing 2,048 full-wave dipoles arranged in sixteen rows of 128 elements. Each row is 470 m long in an E-W direction and the N-S extent of the array is 45 m. Time-scanning is employed to allow the reception pattern in declination and θ (azimuth) to cover the whole of the declination band and θ from -90° to $+90^{\circ}$. Time-scanning receivers are employed and the two halves of the aerial are combined in an E-W interferometer. Each row of dipole elements is backed by a tilted reflecting screen so that maximum sensitivity is obtained at a declination of approximately $+30^{\circ}$, the overall sensitivity being reduced by more than one-half when the beam is scanned to declinations above 40° and below -10° . The bandwidth of the array to half intensity is about $\pm 1^{\circ}$ in right ascension and $\pm 2^{\circ}$ in declination; the phasing arrangement is designed to produce beams at roughly 2° intervals in declination with a time constant of 0.1 s. The flux densities correspond to a flux density of 0.5×10^{-26} W m $^{-2}$ Hz $^{-1}$. For detailed studies of the pulsating source a time constant of 0.05 s was usually employed and the signals were displayed on a multi-channel "teletypewriter" receiver with a time constant of 0.05 s. Accurate timing of the pulses was achieved by recording second pipe derived from the MOP Rugby time-transmission. A record obtained when the pulsating source was un-

NATURE, VOL. 217, FEBRUARY 24, 1968

Earliest Physical Interpretations of the Phenomenon

1. Stellar Oscillations such as are seen in white dwarfs
2. Little Green Men (LGM). The whimsical characterization of the scruff suggested in the discovery paper as indicative of the possibility of broadcast signals from other civilizations.

What Led to Jocelyn Bell Burnell's Achievement?

1. Survey conducted with high time resolution
2. Survey telescope of sufficient size to detect weak sources with the very short integration times being used
3. Survey repetition over long time duration (many months) so that multiple observations are made at each point in the sky
4. Conscientious attention to the need to understand subtle effects in the data

A.A. Penzias and R. W. Wilson Discovery of the Cosmic Microwave Background



A.A. Penzias and R. W. Wilson Discovery of the Cosmic Microwave Background

Background:

Arno Penzias: Joined AT&T Bell Labs as a fresh Princeton PhD in 1962 with a desire to continue his thesis research which was a search for HI 21-cm emission from clusters of galaxies. Built the cold load

Robert Wilson: Joined AT&T Bell Labs as a fresh Caltech PhD in 1963 with a desire to continue his thesis research which was a search for the radio halo of the Milky Way. Rebuilt the receiver.

Penzias and Wilson were the only radio astronomers at Bell Labs

(From Serendipitous Discoveries in Radio Astronomy, ed. K. Kellermann and B. Sheets.)

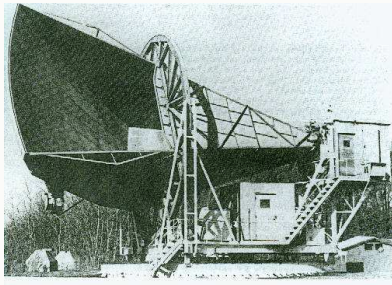
The Telescope: A 20-Foot Horn Reflector Used for Project Echo

The horn-reflector was conceived and built by Harald Friis, the same person who designed and built Jansky's antenna.

The horn-reflector was invented for communications purposes because it has extremely low sidelobe response.

- ▶ The aperture is unblocked
- ▶ The gain response can be accurately calculated and measured
- ▶ Pointed upward, the receiver is shielded from the ground; the sidelobe/backlobe response is very low.

20-Foot Echo Horn Antenna



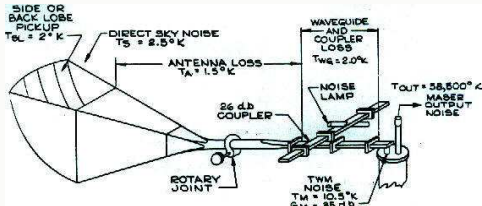
The Receiver: A 6-GHz, Dicke-Switched, Traveling-Wave Maser Radiometer

The Echo receiver was adapted to the needs of radio astronomy

During Project Echo the system temperature was computed to be:

Sky (at zenith)	$2.3 \pm 0.2 \text{ K}$
Horn antenna	$2.0 \pm 1.0 \text{ K}$
Waveguide	$7.0 \pm 0.7 \text{ K}$
Maser assembly	$7.0 \pm 1.0 \text{ K}$
Converter	$0.6 \pm 0.2 \text{ K}$
Total System Temperature	$18.9 \pm 3.0 \text{ K}$

Echo project assigned noise contributions to various components of the 6 GHz system



Sky Temperature Measurements

1. Echo tipping scans consistently gave
 $T_{\text{sys}} = 22.2 \pm 1.0 \text{ K}$

These results were reproduced by Penzias and Wilson at 4.1 GHz

2. Penzias and Wilson switched the radiometer between the 4.2 K helium cold load and the antenna as the antenna scanned in elevation. Saw that the sky temperature matched the cold load temperature at 40 degrees elevation with 0.04 db of attenuation ($\sim 7.5 \text{ K}$ total radiation temperature. This was qualitatively unexpected, the antenna should not be warmer than the cold load!

Possible Explanations

1. The atmospheric emission at 4.1 GHz was much greater than expected
 - Tipping scans ruled this out
2. RFI contributions
 - Repeated scans in elevation over day ruled this out
3. Unresolved sources in the Milky Way
 - Spectral extrapolations from source surveys at lower frequencies made this unlikely
4. Radiation from the walls of the antenna
 - Measurements of ohmic losses, and measurements over an entire year ruled this out

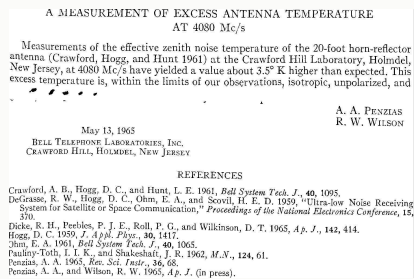
The Explanation: Consult Experts!

Ken Turner (a former NAIC staff scientist) heard of the result and mentioned it to his DTM colleague, Bernie Burke, who phoned Arno and encouraged him to contact Bob Dicke.

Dicke provided the cosmological interpretation to the observations that was in fact the solution to an astrophysical problem of long-standing.

Penzias and Wilson published their result.

Penzias and Wilson Publication ApJ Letters vol. 142, p.419 (1965)



A Digression: The Cosmological Debate of the mid 20th Century

Forty years ago, one of the major astrophysical questions was whether the universe was evolving from a "big bang" or whether it was in a steady state. Both ideas had vocal proponents, neither had much in the way of observational proof.

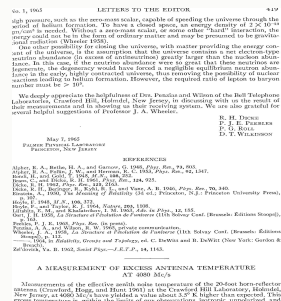
A few consensus ideas existed that maintained the perpetuity of the universe without recourse to a steady state explanation. Robert Dicke espoused one of these, the 'oscillating' universe.

A Digression: The Cosmological Debate of the mid 20th Century

The primary difference between any cosmological model with a "bang" and one without is that the bang models leave residual radiation as a permanent record of the bang. In an expanding universe this radiation cools with the expansion ultimately becoming a dominate contributor to the microwave background.

As Penzias and Wilson were making their observations at Bell Labs, Dicke, Wilkinson and Peebles were initiating experiments at Princeton to search specifically for the CMB.

The paper interpreting the results from the CMB discovery preceded the report of the observation



Another Digression: The Excitation of CN

In 1938 (!) S. W. Adams discovered absorption lines from interstellar cyanogen (CN) molecules in stellar spectra. Andrew McKellar computed the CN excitation temperature from the line strengths and concluded that it was 2.3 K, a value that appeared to be constant from CN absorption lines in the spectra of all stars in which the interstellar CN absorption lines were seen. The source of the excitation was a mystery, and remained a well-known mystery, until 1965 when the CMB was revealed.

Immediately after the Penzias and Wilson result was announced, observations were made of the CN 2.6 mm spectral line providing strong support for the CMB observations.

What Led to Penzias and Wilson's Achievement?

1. Pursuit of a precision measurement using/building equipment capable of providing the required precision.
2. Sufficient access to the telescope to conduct confirming observations, and make tests, over a long period of time.
3. Conscientious attention to the need to understand subtle effects in the data.
4. Advice of experts.

R. W. Wilson, K. B. Jefferts, and A. A. Penzias The Discovery of Carbon Monoxide

Annual Review of Astronomy and Astrophysics

Vol. 7, 1968

HYDROGEN MOLECULES IN ASTRONOMY*

By G. H. FURUKAWA, B. SOMMERVILLE, and K. DREIER†

†Present address: University of California, Berkeley, Calif. 94720

*This paper is abstracted from a study that the astronomical elements H, O, and N will frequently form molecules. (See the separate discussion on H₂.)

1. INTRODUCTION

The interest in the hydrogen molecule, H₂, stems from the fact that it is the stable form of hydrogen at low temperatures. Its dissociation energy is that of atomic hydrogen is given by the dissociation energy $D_0(\text{H}_2)$

$$D_0(\text{H}_2) = 4.48 \text{ eV} = 104,360 \text{ cal/mole} \quad (1.1)$$

It is concluded that local thermodynamic equilibrium applies. For the densities appropriate to stellar atmospheres, Equation 1.1 implies that $D_0(\text{H}_2) > kT$ for main-sequence stars later than A4 (T = 10,000°K) and for giant stars later than M7 (T = 3,400°K). H₂ is expected to be dominant in planetary atmospheres.

It is believed that the kinetic temperature throughout large regions of interstellar space is of the order of 100°K and that the density is of the order of 10¹⁰ cm⁻³, so that one would expect H₂ to dominate there also, in the sense of Equation 1.1. However, the phenomena which from the data derived are very different. It is found on the surface of grains whose temperature is about 10°K, which is in agreement with interstellar space, where other temperatures are about 30,000°K. Under such conditions from thermodynamic principles, Equation 1.1 is inapplicable. Rather, detailed calculations of rates of formation and destruction are required, as reported by Sommers (1961), Spitzer (1955), and van de Hulst (1957). At the present time such calculations are still incomplete. It is believed that H₂ dominates in at least limited regions of interstellar space.

Gold & Salpeter (1967) consider that the presence in interstellar space of H₂ is about 10⁻⁵ times that of H.

The energy of ionization for this review was calculated in October 1965.

Present address: Berkeley Astronomy Department, University of California, Berkeley, California.

†Present address: Astronomy Department, University College London, London, England.

*Work supported in part by the National Aeronautics and Space Administration, under Grant NS42-141.

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FURUKAWA, SOMMERVILLE, & LIFENBERG

Dissociation fractions owing to inadequate knowledge of the thermodynamic functions of H₂ at high temperatures.

2.5 INTERSTELLAR SPACE

At this writing there is still no observational evidence that appreciable amounts of H₂ occur in interstellar space. The calculations of Gold & Salpeter (1967), which predict a value of about unity for the H₂/H ratio, are uncertain by a factor of ten.

It might be thought that radiative association, H + H → H₂, would convert any atomic hydrogen present to the molecular form in a relatively short time. Collisions between H atoms occur about every 10¹⁰ seconds under typical conditions in interstellar space, so that each atom has experienced some 3 × 10¹⁰ collisions during the lifetime of the Galaxy. Each collision lasts about 10⁻¹⁶ seconds, giving a total duration of 3 × 10⁴ seconds during which each atom is in collision. If the collision partners (H(1S) + H(1S)) form a 2_g⁺ state at large separations, an infrared transition down to a bound vibrational level of the same electronic state can occur; however, the transition probability is probably much less than that of the 1-0 transition (10⁻⁷ sec⁻¹) because of unfavorable overlap of the vibrational wave functions. The chance for an atom to form a molecule this way is therefore less than 3 × 10⁻¹⁶ over the entire lifetime of the Galaxy.

If the collision partners form a 2_g⁺ state, transitions to the ground 2_g⁺ electronic state are permitted by all selection rules except ΔS = 0. As pointed out by Gold & Salpeter (1967), this rule can be violated only by spin-orbit mixing. According to Section 4.1, this can occur through the spin-spin interaction of the 2_g⁺ state, which admixes a percentage of singlet into that state of order $H_{21}/(2E_{21})$, where E_{21} is the fine structure constant. The square of the dipole matrix element is therefore reduced from the value for a permitted transition by about 10^{-10} . At 100°K, the separation between the two electronic states at closest approach on the repulsive curve corresponds to the emission of a photon near 100 μ, giving a transition probability of order 10⁻¹⁰ sec⁻¹. Although this is much larger than that of the quadrupole process, it still leads to an overall probability of only 10⁻¹⁶. We conclude that arguments for H₂ abundance based on Equation 1.1, such as that of Zwick (1953), cannot be trusted unless a much faster process can be found.

It might be thought that H and H could undergo radiative association more easily because HD possesses a small dipole moment. Since the 1-0 band of HD is about 200 times stronger than that of H₂, the overall probability of radiative association through the 2_g⁺ state of a atom with a passing H atom might be raised to 6 × 10⁻¹⁰—still negligible. The rate of association through the 2_g⁺ state is unchanged.

Van de Hulst (1957) was the first to point out that H₂ could form on the surface of interstellar grains. If H atoms striking a grain readily stick to it for a considerable period, a layer of atoms is built up so that from time to

R. W. Wilson, K. B. Jefferts, and A. A. Penzias The Discovery of Carbon Monoxide

Background:

In 1970, the existence of interstellar molecules in dense regions of the interstellar medium was well established.

- ▶ OH and H₂O were known to be exceptionally bright masers in regions of active star formation
- ▶ Thermal OH was being mapped the disk of the Milky Way and found to be present in dense gas
- ▶ Formaldehyde, H₂CO, had been detected
- ▶ The molecular chemistry of the interstellar medium was known to be organic.

But there was no widely-distributed, bright, spectral tracer of molecular gas, nothing equivalent to the HI 21-cm line for atomic gas.

Why Carbon Monoxide?

1. CO was known to be readily produced by ion-molecule reactions in the gas phase.
2. It was expected to be abundant in the ISM because its atomic constituents are among the most abundant heavy elements in the cosmos, both ~0.1% of H
3. CO has a photodissociation potential, and a photoionization potential greater than the Ly-α energy → CO can exist near early-type stars.
4. CO is shielded from continuum photoionization and photodissociation by H₂.

**U.S. Radio Astronomy 70-years After
Jansky**

