Cosmic Masers

by

Jim Moran

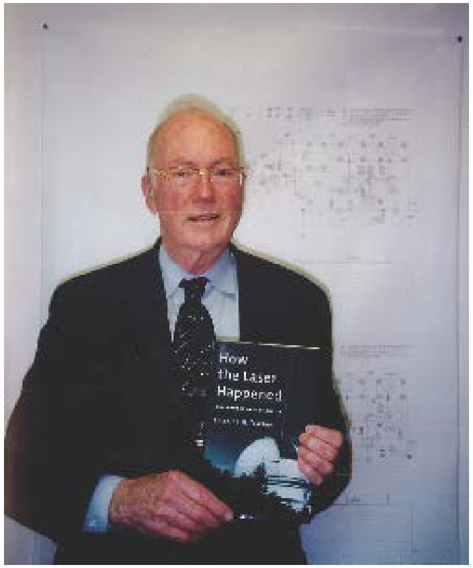
Harvard-Smithsonian Center for Astrophysics

The Golden Years of Radio Astronomy

IAU General Assembly, Honolulu

August 5, 2015

Charles H. Townes (1915–2015)*
His Legacy in Cosmic Masers



1944 Warned management at MIT Rad Lab that the 1.25 cm airborne radar developed for the South Pacific theater would not work (because of atmospheric H_2O). It failed.

1946 Measured precise frequency of 1.35 cm H_2O line

1954 Presented case for observing spectral lines of molecules via radio astronomy (Washington Conference on Radio Astronomy)

1959 Measured precise frequency of ground state of OH, enabling his former student, Alan Barrett, to detect it in ISM in 1963

1964 Invented laboratory maser
- Spinoffs essential for VLBI at 22 GHz:
- Low-noise maser amplifier
- Hydrogen maser frequency standard

1969 Discovered cosmic H2O masers at Berkeley (with Cheung, Rank, Thornton, and Welch)

*Academic tree: von Helmholtz (Berlin, 1843) ⟶ Michelson (Berlin) ⟶ Gale (Chicago) ⟶ Smythe (Chicago) ⟶ Townes (Caltech) ⟶ Barrett (Columbia) ⟶ Moran (MIT)

I Should Have Followed Up on That …

PHYSICAL PROCESSES IN GASEOUS NEBULAE

1. ABSORPTION AND EMISSION OF RADIATION

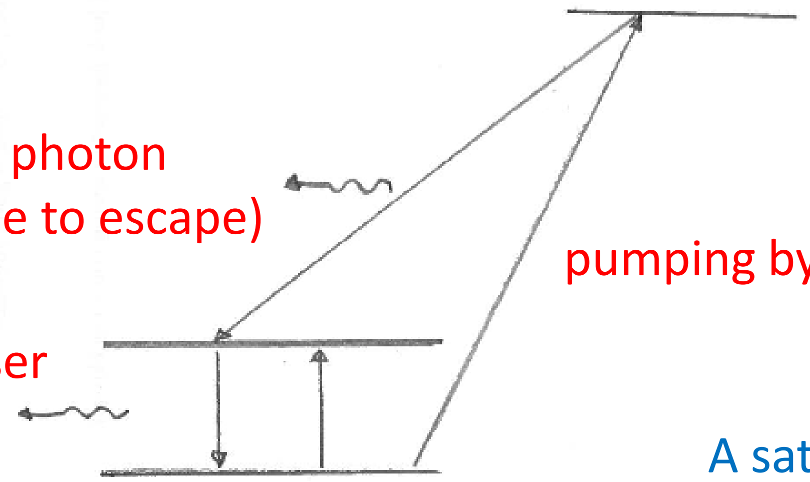
DONALD H. MENZEL

ApJ, 85, 330, 1937

The total radiation, absorbed in the transition $n' - n$, including the effect of the "stimulated emissions," which must be counted as negative absorptions, is easily found to be . . . .

Outside of thermodynamic equilibrium, the condition may conceivably arise when the value of the integral [above] turns out to be negative. The physical significance of such a result is that energy is emitted rather than absorbed. This energy must be distinguished, however, from that arising in random emissions. The process merely puts energy back into the original beam, as if the atmosphere had a negative opacity. This extreme will probably never occur in practice.

Elementary Maser Pumping Scheme



waste pump photon
(must be able to escape)

pumping by radiation or collisions

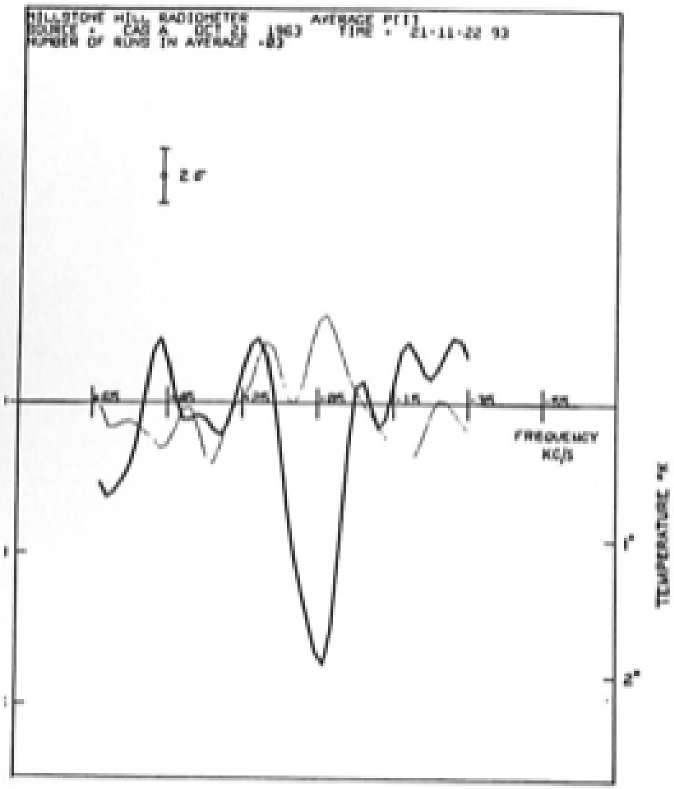
microwave maser
photon

A saturated maser requires
one pump photon per
microwave maser photon

“Spectacular” cosmic masers require population inversion AND **high** negative optical depth, aka “gain,” e.g., as seen in OH, H_2O, SiO, and CH_3OH.

Discovery of OH at 18 cm in ISM in 1963

Cassiopeia A



Antenna Temperature

Velocity (km/s)

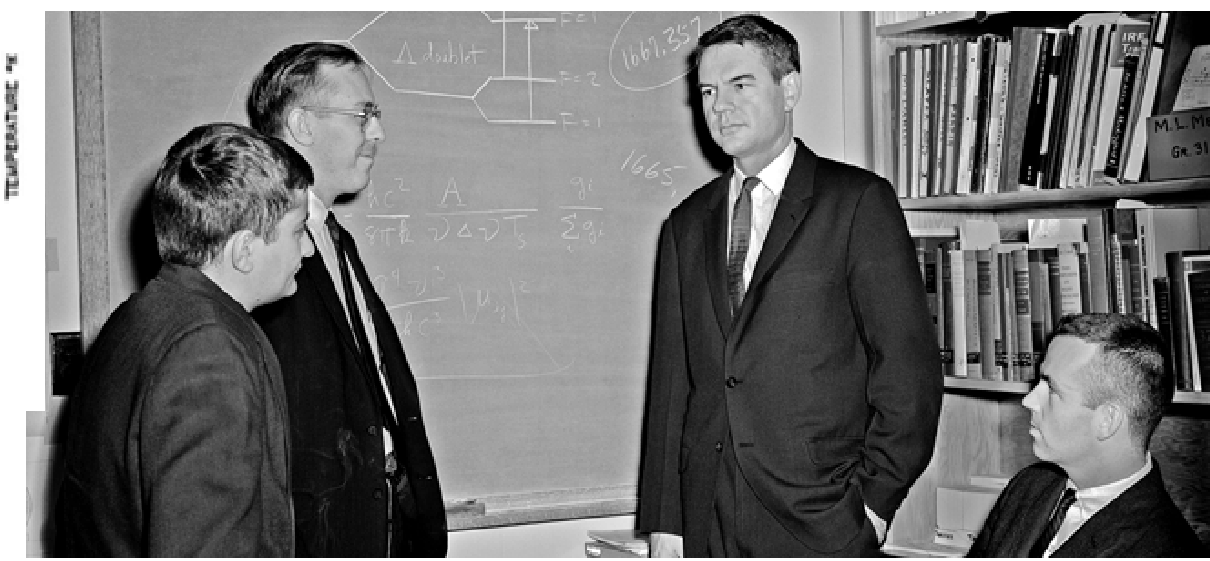
Spectrum made with Weinreb's digital autocorrelator built for his PhD thesis

Al Barrett

Lit Meeks

Sandy Weinreb

John Henry



NATURE October 2, 1965 VOL. 209

OBSERVATIONS OF A STRONG UNIDENTIFIED MICROWAVE LINE AND OF EMISSION FROM THE OH MOLECULE

By PROF. HAROLD WEAVER, DR. DAVID R. W. WILLIAMS, DR. N. H. DIETER and W. T. LUM
Radio Astronomy Laboratory, University of California, Berkeley

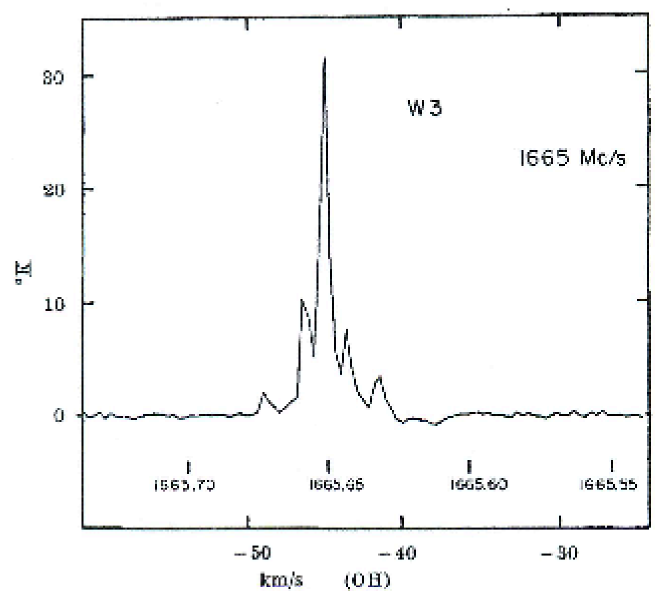


Fig. 2. Spectrum of W3 at 1,665 Mc/s with a resolution of 2 kc/s (0·4 km/sec)

There is no known identification of the strong emission line at 1,665 Mc/s shown in Fig. 1. In what follows, for brevity in writing and to emphasize the surprising nature of the observation just presented, we shall speak of this unidentified line as arising from 'mysterium'.

CSIRO

DIVISION OF RADIOPHYSICS

UNIVERSITY GROUNDS, CITY ROAD, CHIPPENDALE, N.S.W. TELEPHONE 68 0066. TELEGRAMS CORESEARCH SYDNEY

A.N.R.A.O.,
P.O. Box 189,
PARKES. N.S.W.

1st October, 1965.

Professor Alan H. Barrett,
Massachusetts Institute of Technology,
Research Laboratory of Electronics,
CAMBRIDGE. MASSACHUSETTS. U.S.A.

Dear Alan,

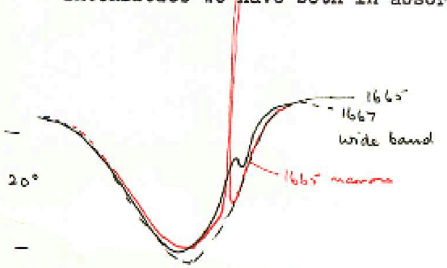
Many thanks for the letter and preprint. I was extremely glad to get it as I am writing a review for "Discovery" and wanted to include something on polarization.

Yes we have had OH in emission for well over a year hidden in our data, at l = 42' b = -3'. It occurred as a small reversal on the side of a deep absorption on 1665 - diluted by (a) a wide band channel of 35 Mc/s and (b) being well out of the beam. It was ignored as a noise fluctuation in the 1964 results but repeated this year when we re-surveyed the whole central region at all four frequencies on a much closer grid. On 10 Mc/s bandwidth it clearly stands out in emission on 1665 and 1612.

We have some very similar results to yours, on W49, a point source we have 1612, 1665 and 1667 but no 1720. On NGC 6334 we have OH 7 minutes of arc displaced from the continuum center. We are preparing a note summarizing all the anomalous intensities we have both in absorption and emission.

With kind regards,
Yours sincerely,

J. G. Bolton.



COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION, AUSTRALIA

OBSERVATIONS OF THE INTERSTELLAR HYDROXYL RADICAL

A thesis presented

by

Ellen Jean Gundermann

to

The Department of Astronomy

Harvard University

Cambridge, Massachusetts

June 1965

Advised by:

Ed Lilley &
Sam Goldstein

8.3 Discovery in W49

The 18-cm OH lines were first seen in emission in April of 1964. They were not found in an area of low continuum radiation, but rather in the direction of the continuum source W49. This source gives an antenna temperature at 1670 Mc/s of 5°K. The coordinates of W49 are approximately $l^{II} = 44°$; $b^{II} = 0°$. It lies in a highly obscured

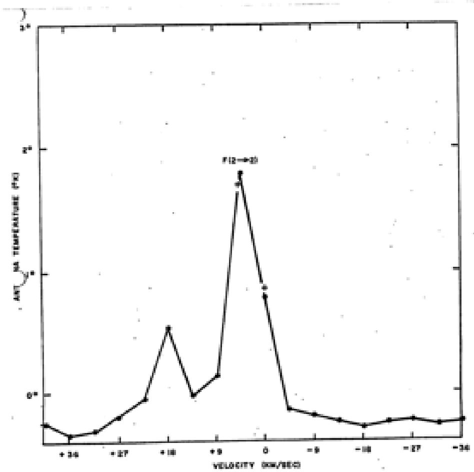
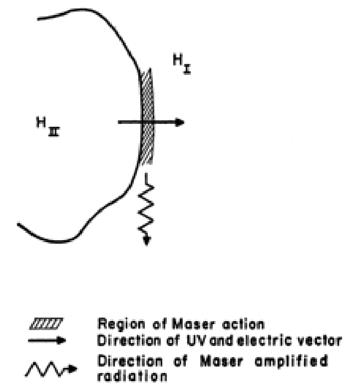


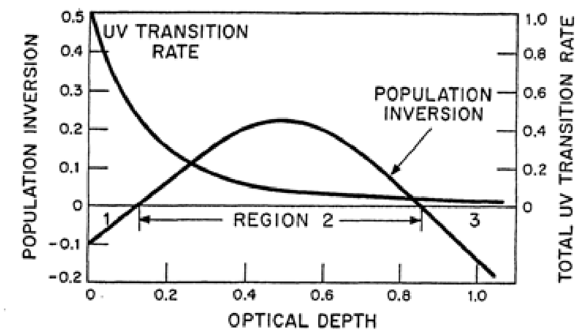
FIGURE 8-2 W49

Theory of Maser Emission

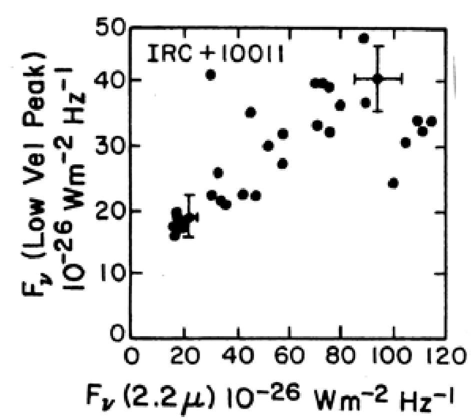
1966 (May) Perkins, Gold & Salpeter (UV)



1966 (Oct.) Litvak, McWorter, Meeks, & Zeiger (UV)

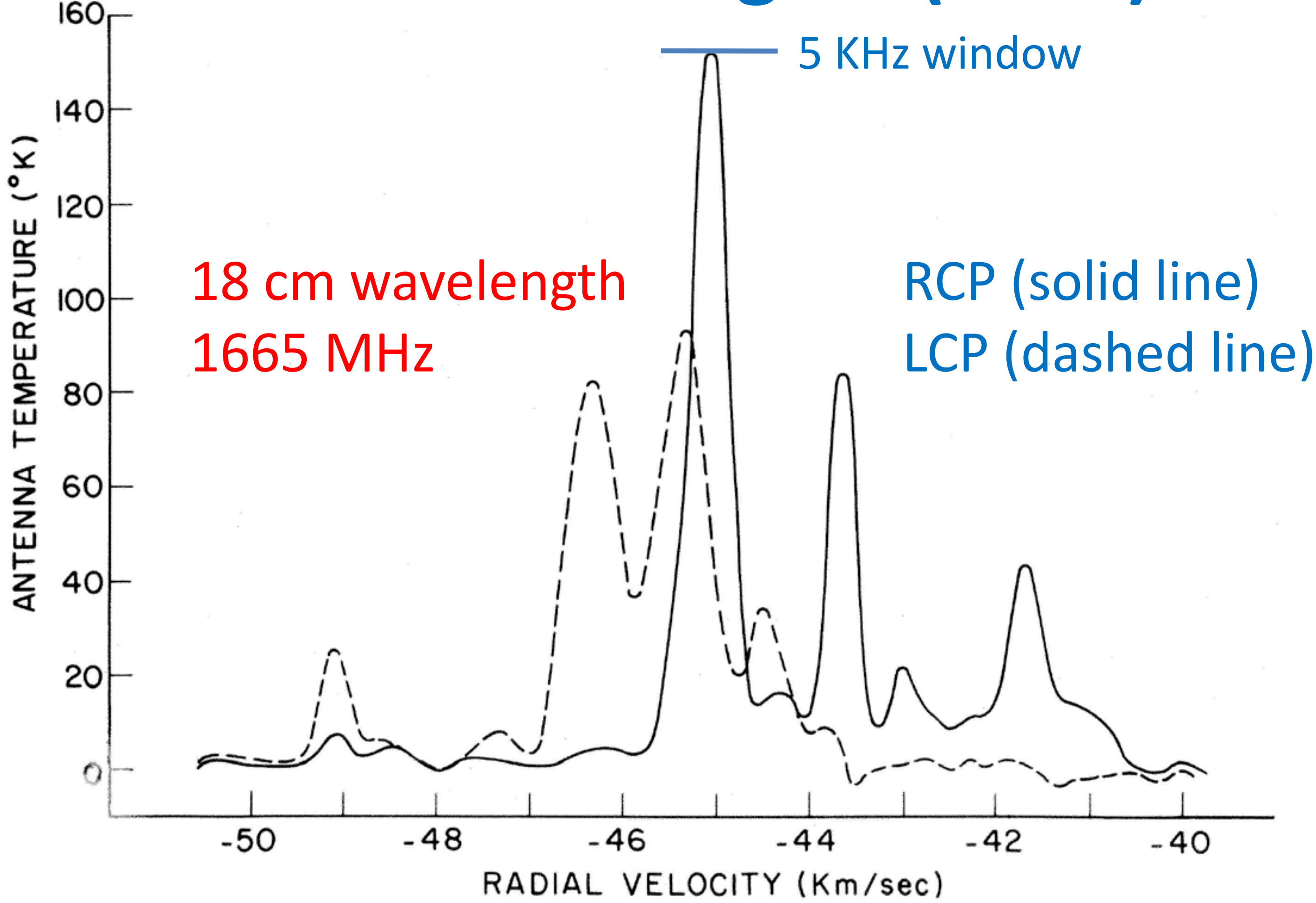


1973 Goldreich, Keeley, & Kwan (IR)*



*Based on data showing correlation of IR and maser flux density in late type stars (Harvey et al., 1973)

Spectrum Toward Westerhout 3 (aka W3), a Galactic HII Region (1966)



Rogers and Barrett, *Nature*, April 1966
Davies, de Jager, & Verschuur, *Nature*, March 1966

Groups Active in OH Maser Research

- CSIRO (Parkes 210 ft)
- Berkeley
- Harvard
- MIT
- Jodrell Bank

Interferometry of OH Maser W3(OH) at 18 cm

Publication date	Interferometer	Baseline (km)	Angular size	Significance	Reference (1st author)
1966 (Aug)	OVRO	1.6	<20″	Abs Position	Cudaback
1966 (Aug)	Haystack-Millstone	0.7	<15″	Abs Position	Rogers
1967 (Mar)	Jodrell Bank-Malvern	127	<0.05″	Sep ~0.1”	Davies
1967 (May)	Millstone-Agassiz	14	<0.3″	First map (3)	Moran
1967 (Aug)	Haystack-GB 140 ft.	845	<0.02″	First VLBI	Moran
1968 (May)	Haystack-GB-Hat Creek	4030	<0.005″	Good map (7)	Moran
1968	Haystack-GB-HC-Onsala	7900	0.0045″	Size	Moran
1971	Jodrell Bank-Malvern	127		Better map (16)	Cooper
1978	GB-NRL-ARO*	3100		B fields	Moran
1980	US NUG	4030		Excellent map (70)	Reid
1982	Merlin	134		Multi-transitions	Norris
1992	US NUG	4030		Proper motions & B field distribution	Bloemhof

*5 cm

(Fall 1966)

PHASE STABILITY CHECK OF AGASSIZ-MILLSTONE INTERFEROMETER USING TEST TRANSMITTER ON FIRETOWER

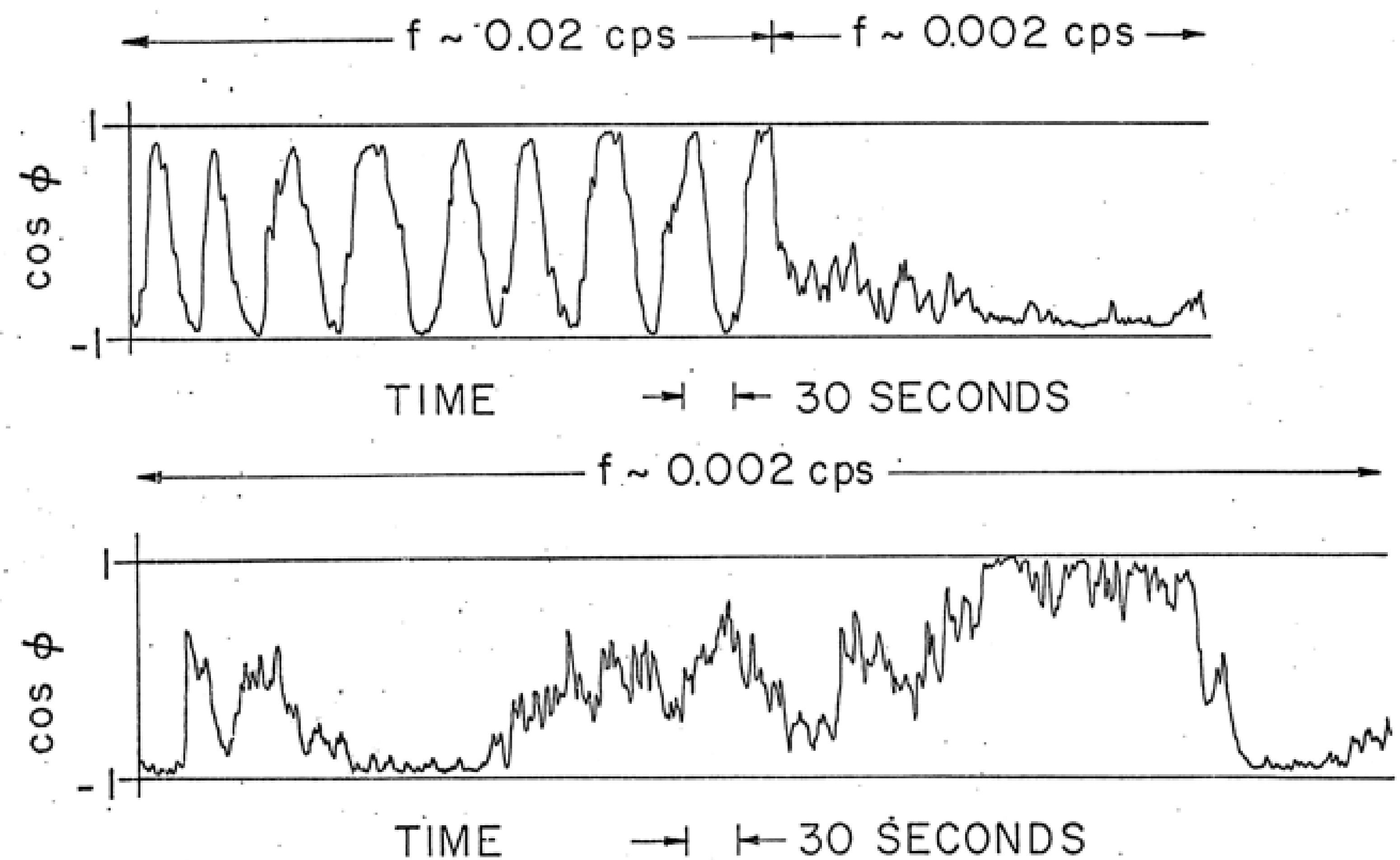
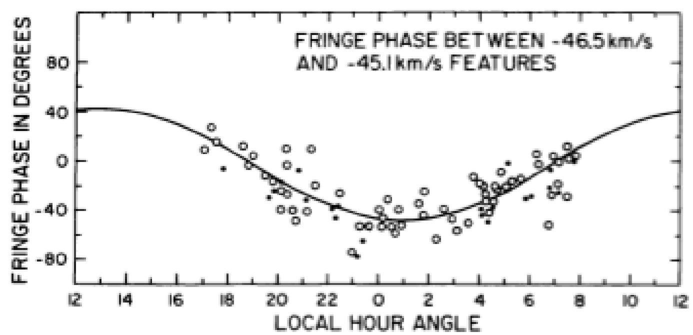


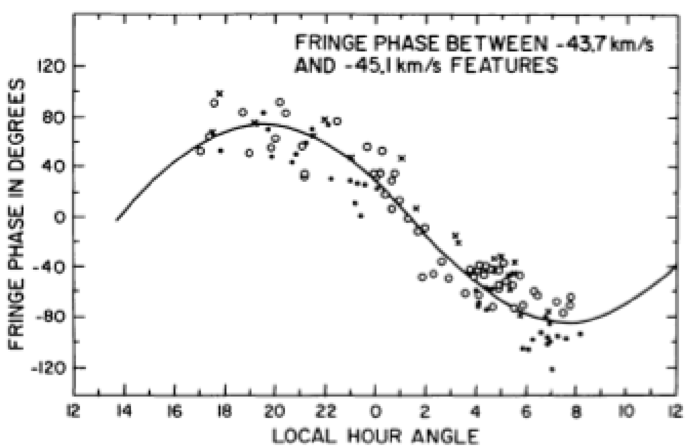
FIGURE 3-5. PHASE STABILITY MEASUREMENTS ON INTERFEROMETER. THE 28.5 MHz LOCAL OSCILLATOR WAS FIRST OFFSET BY 0.02 Hz AND THEN SET TO EXACTLY 28.5 MHz.

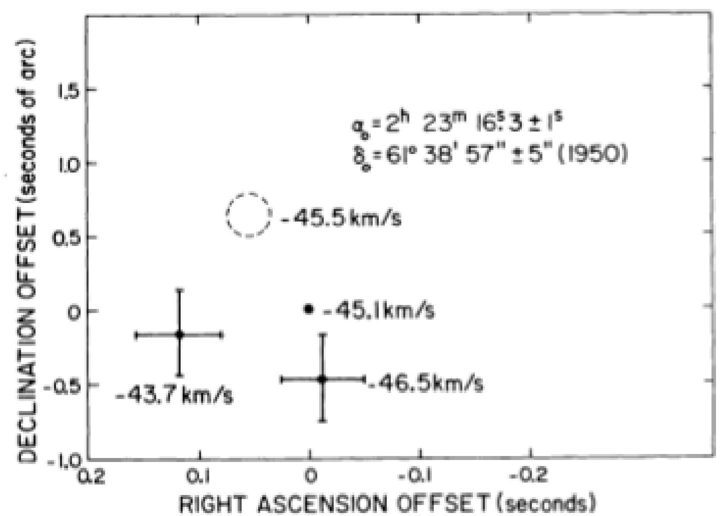
First Maser "Spot Map" Millstone–Agassiz Interferometer (1967): W3(OH)

Visibility Phase vs. Hour Angle

$$\Delta\phi = \omega_0 \frac{D}{C} \{[\sin\delta_B \cos\delta_S - \cos\delta_B \sin\delta_S \cos(L_S - L_B)]\Delta\delta$$
$$+[\cos\delta_B \cos\delta_S \sin(L_S - L_B)]\Delta\alpha\} ,$$







Some Considerations
for a
Very Long Baseline Interferometer

AIO - NRAO

M. Cohen, D. Jauncey, AIO, Cornell University

B. Clark, K. Kellermann, NRAO

November 22, 1965

are at radio frequencies which can readily be multiplied up to the desired operating frequency.

It should be stressed that there will be no intent to recover any phase information from the interferometer. In order to measure the angular extent of the source, it is sufficient to measure the amplitude of the fringe visibility alone. Thus, only sufficient phase stability is needed to maintain coherence. It appears that the short term stability of the oscillators may be good enough for several minutes of coherent integration.

Time Keeping

If the i.f. bandwidth is 300 kilocycles, it will be necessary to have the times at the two observatories synchronized to better than one microsecond. This can be achieved by using the atomic standards used to derive the LO frequency, since these can provide a time reference which drifts by only about 1 microsecond per day. Once the time difference between the two clocks is established,

... drift may be determined directly

TO: G. H. Pettengill and P. B. Sebring

FROM: J. M. Moran, B. F. Burke, and J. C. Carter

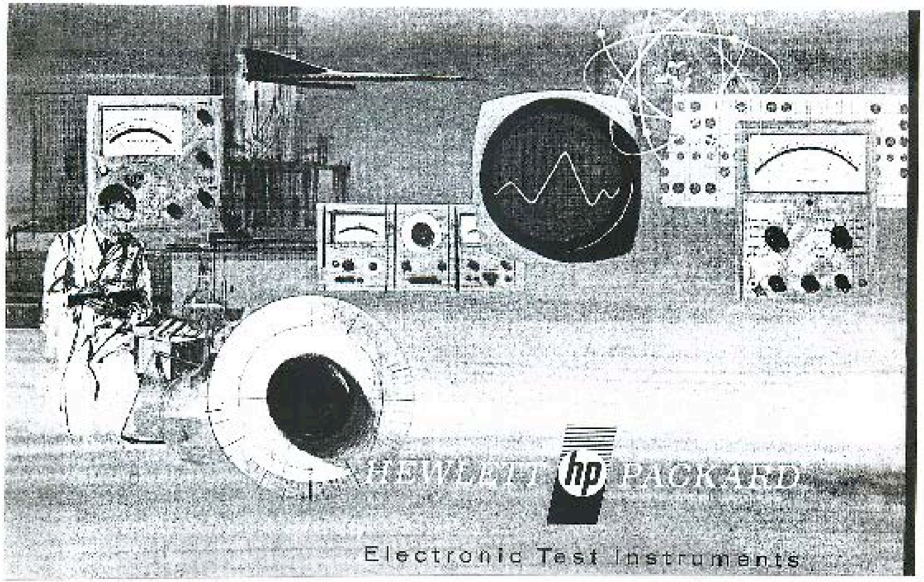
SUBJECT: Proposal for an OH Interferometer Experiment Between Lincoln Laboratory and the National Radio Astronomy Observatory.

DATE: 5 April 1967

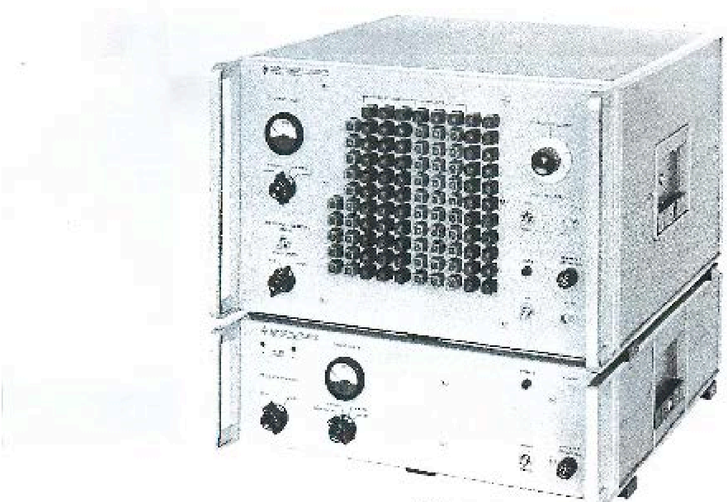
The frequency stability necessary at 1.6 GHz over a 10-second period allowing for 60° phase shift is 1×10^{-10}. We therefore have at least a factor of 3 margin if the additional phase noise in the frequency multiplier chain is made small. This can be done.

The synchronization of the data tapes presents no problem at all at 5 kHz bandwidth since the sampling interval is 100 microseconds. At 100 kHz bandwid the interval is 5 microseconds. This time accuracy should be achievable by carefully monitoring LORAN C for several days. In any event, the timing uncer tainty is small enough to be included in the normal power spectrum analysis. The maximum geometric delay between the signals is about 2 milliseconds.

Hewlett-Packard Catalog circa 1967



Since its founding in Palo Alto, California, in 1939, Hewlett-Packard has grown from a two-man operation into a world-wide organization of more than 7000 people, with an annual sales volume exceeding $125 million.



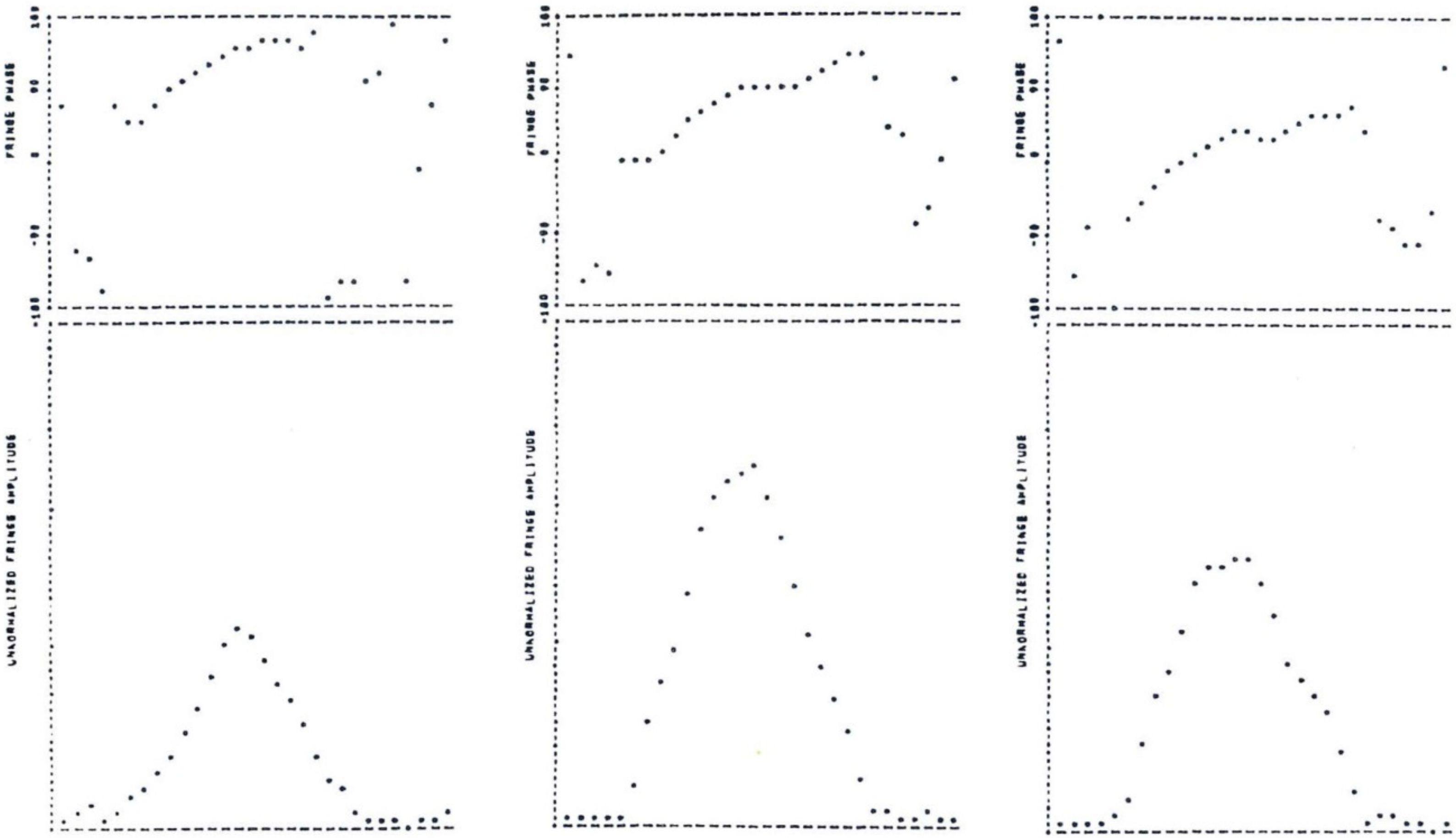
5100A 5110A

HP 5100
Phase-locked oscillator
0-50 MHz in steps of 0.01 Hz

First VLBI Fringes on a Maser Source, June 1967
Haystack 37-m to NRAO 43-m (845 km baseline)

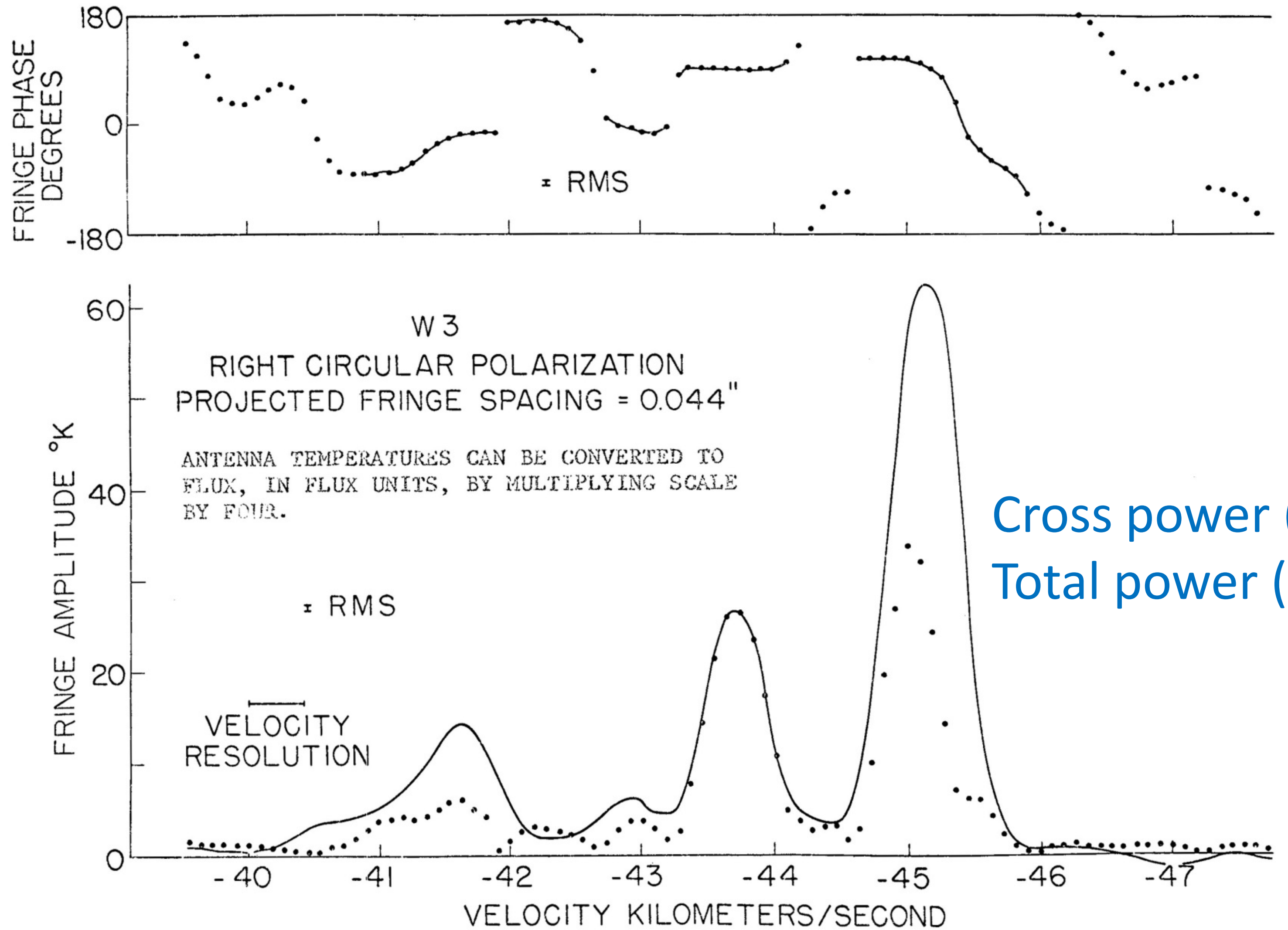
Phase

Amplitude



Frequency (5 KHz window)

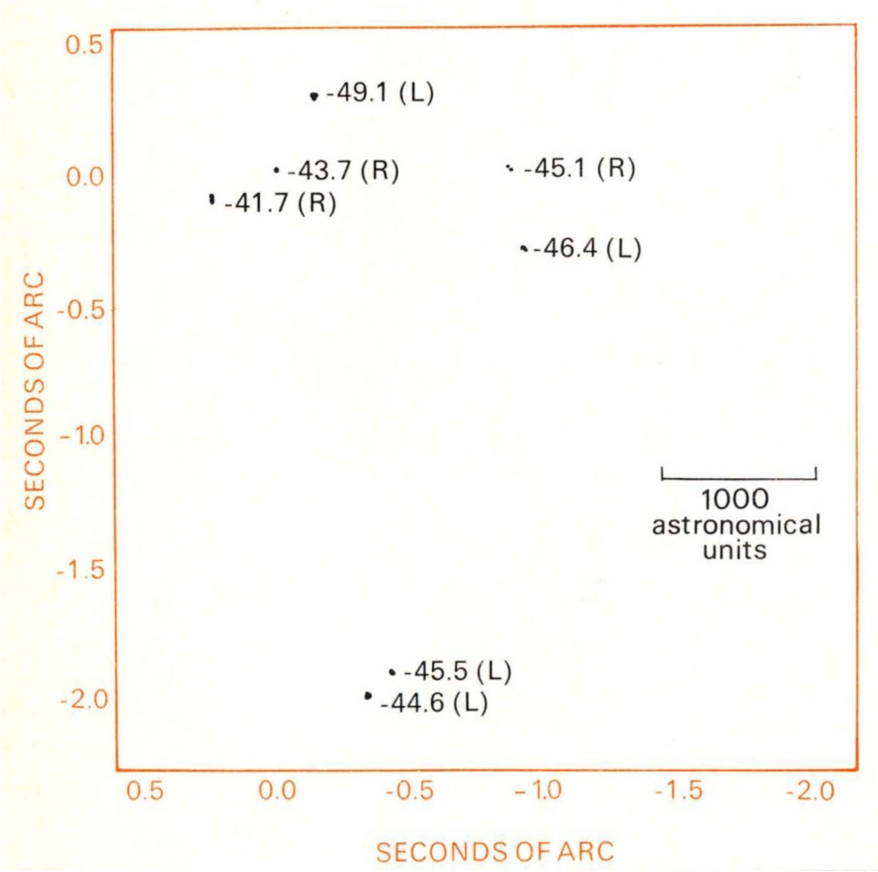
Interferometer Spectrum of W3 in 120 KHz Band (June 1967)

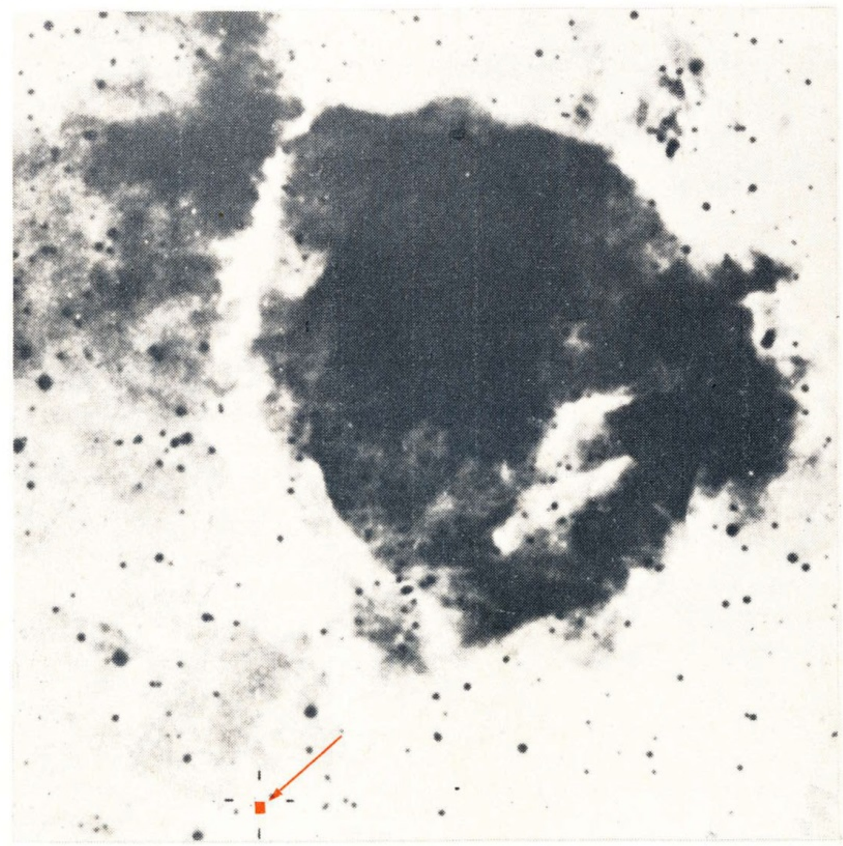


Cross power (solid)
Total power (dotted)

VLBI Image of W3 Maser

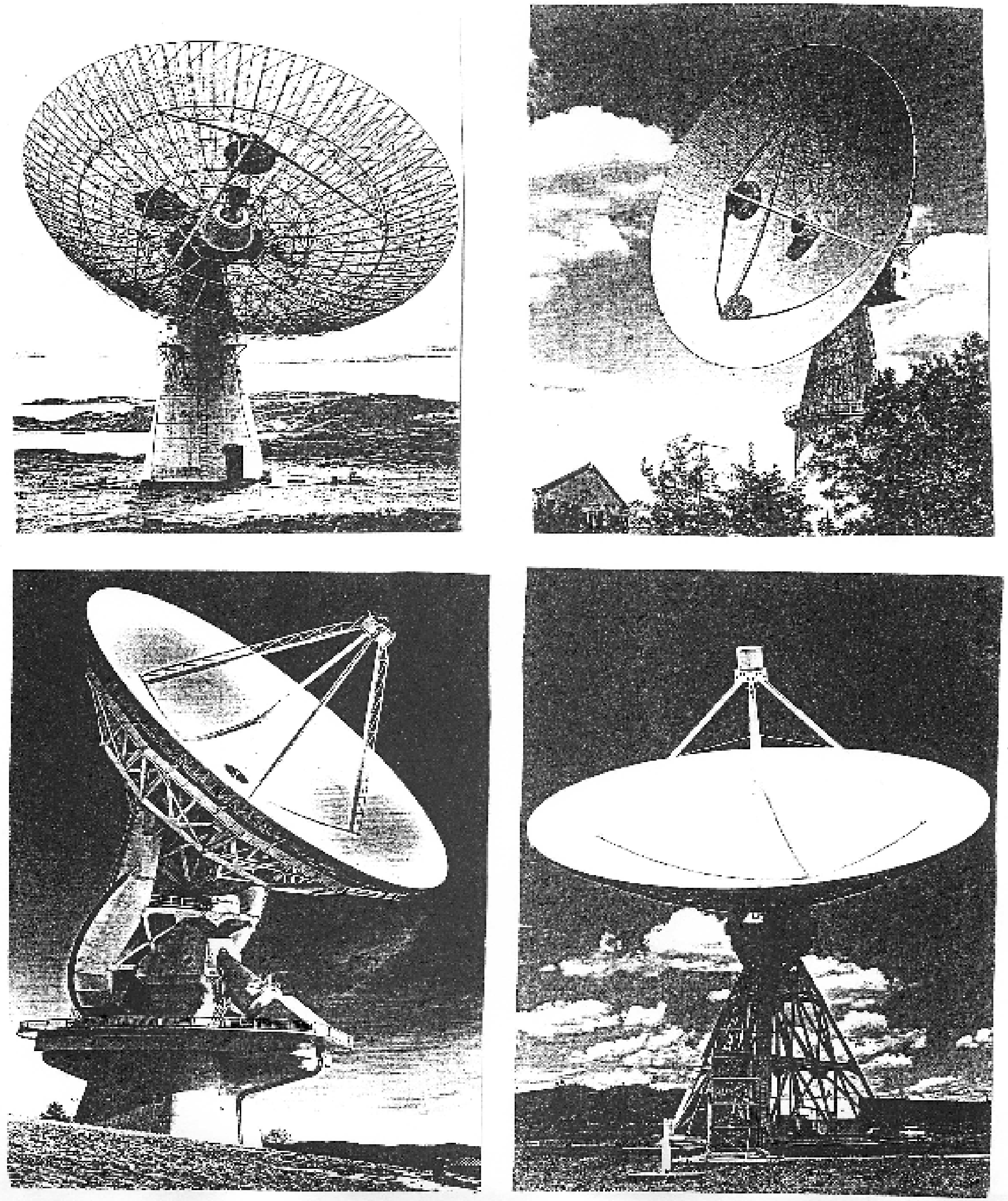
Palomar Sky Survey Image of W3 HII Region



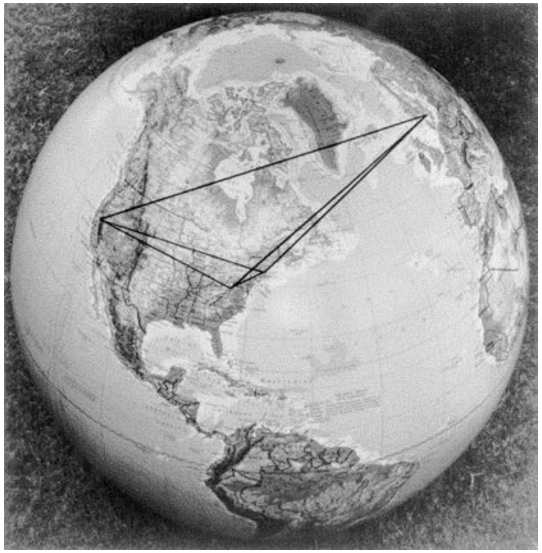


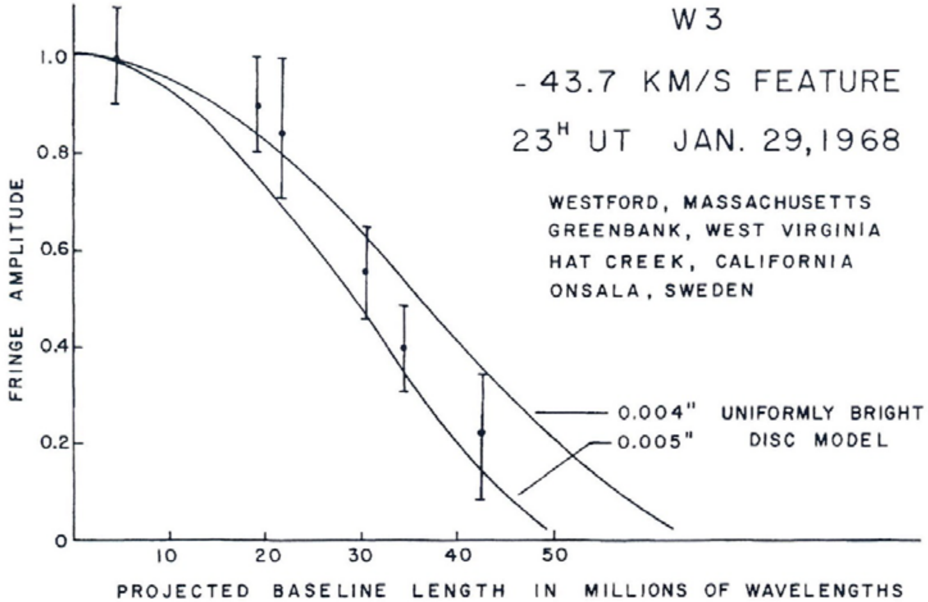
First Four-Element VLBI Array (Jan. 1968)

Onsala
Millstone Hill
Hat Creek
Green Bank



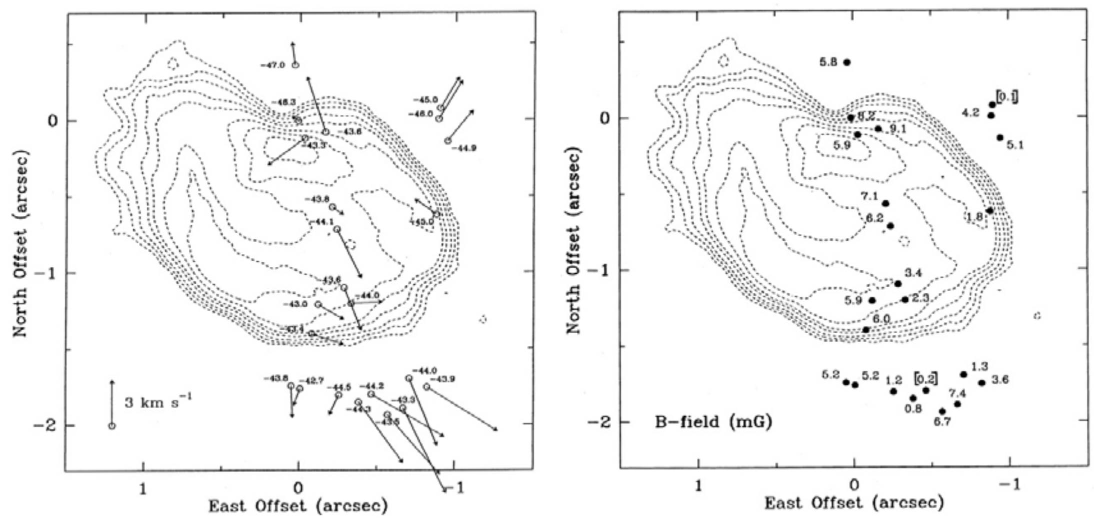
First Resolution of a Maser "Spot"

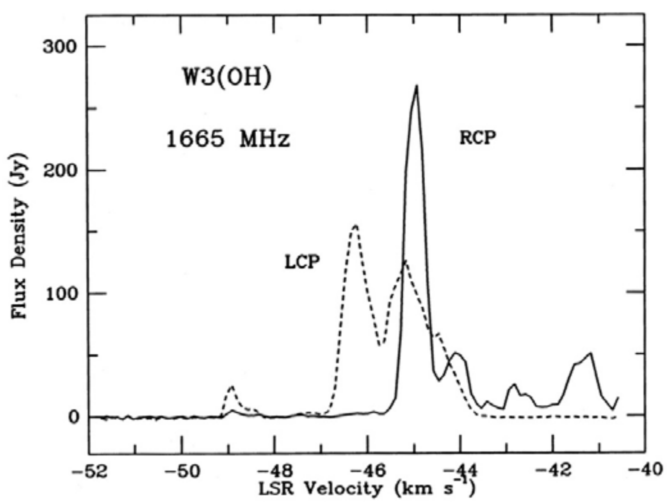




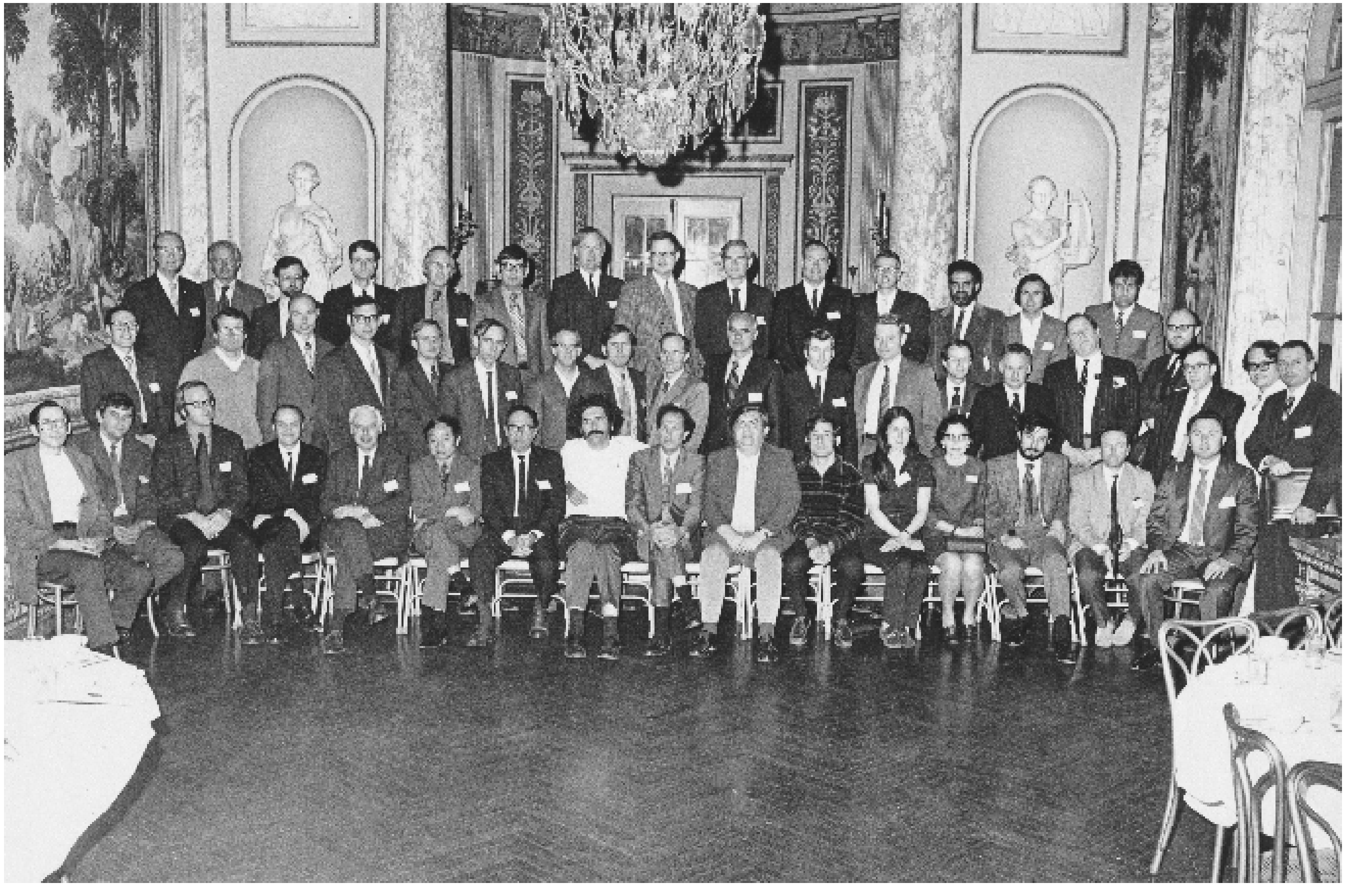
Proper Motions (left) **and Magnetic Field Strength** (right) **in W3 OH Maser (1986) with US VLBI Network (NUG)**

Contours
Trace
UCUII
Region
W3(OH)





Rumford Prize Symposium, April 1971



NRAO-Cornell Group

Claude C. Bare
Barry G. Clark
Marshall H. Cohen
David L. Jauncey
Kenneth I. Kellermann

MIT Group

John A. Ball
Alan H. Barrett
Bernard F. Burke
Joseph C. Carter
Patricia Crowley
James M. Moran
Alan E.E. Rogers

Canadian Group

Norman W. Broten
Richard M. Chisholm
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Herbert P. Gush
Thomas H. Legg
Jack L. Locke
Charles W. McLeish
Roger S. Richards
Jun Lin (Alan) Yen