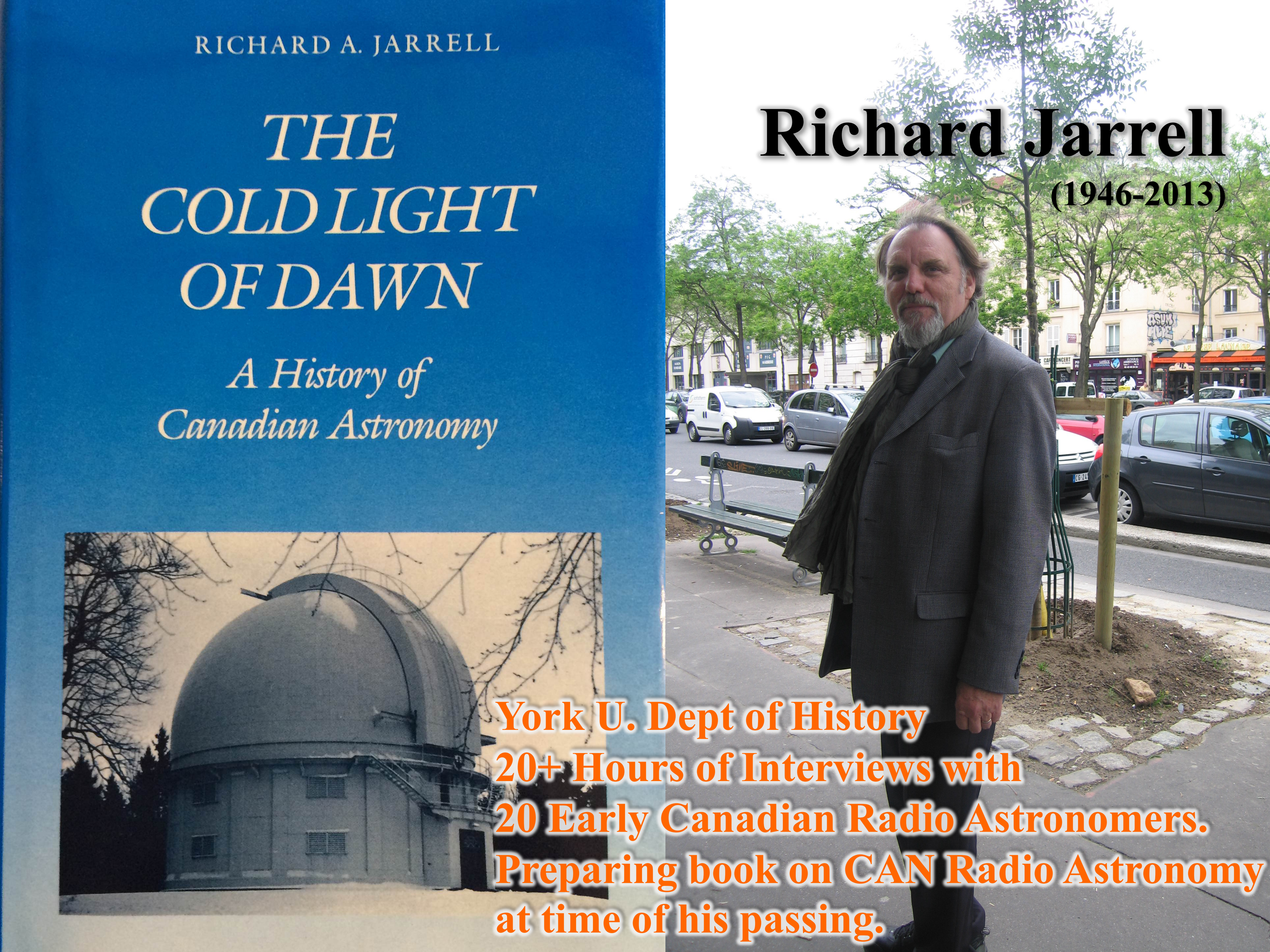
The Foundations of Canadian Radio Astronomy

Tim Robishaw
DRAO

A Workshop on the History of Canadian Radio Astronomy

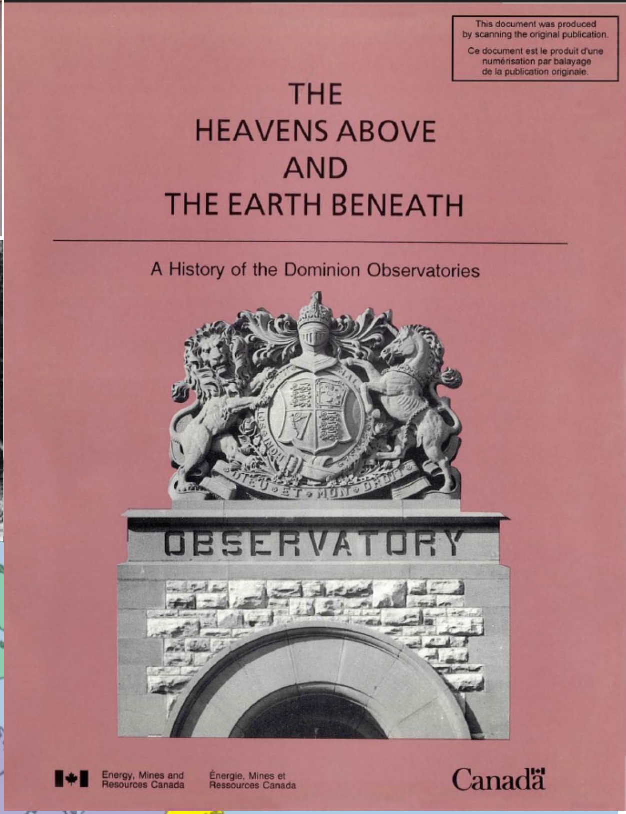
July 25-26, 2016

http://astroherzberg.org/radiohistory2016/


RICHARD A. JARRELL
THE COLD LIGHT OF DAWN
A History of Canadian Astronomy
Richard Jarrell
(1946-2013)
York U. Dept of History
20+ Hours of Interviews with
20 Early Canadian Radio Astronomers.
Preparing book on CAN Radio Astronomy
at time of his passing.

Surveying


DOMINION RADIO
ASTROPHYSICAL OBSERVATORY
DEPARTMENT OF MINES AND TECHNICAL SURVEYS
UNAUTHORIZED VEHICLES ARE NOT
PERMITTED BEYOND THIS POINT, BUT
VISITORS ARE WELCOME TO PROCEED ON FOOT...
PLEASE TURN OFF YOUR CAR ENGINE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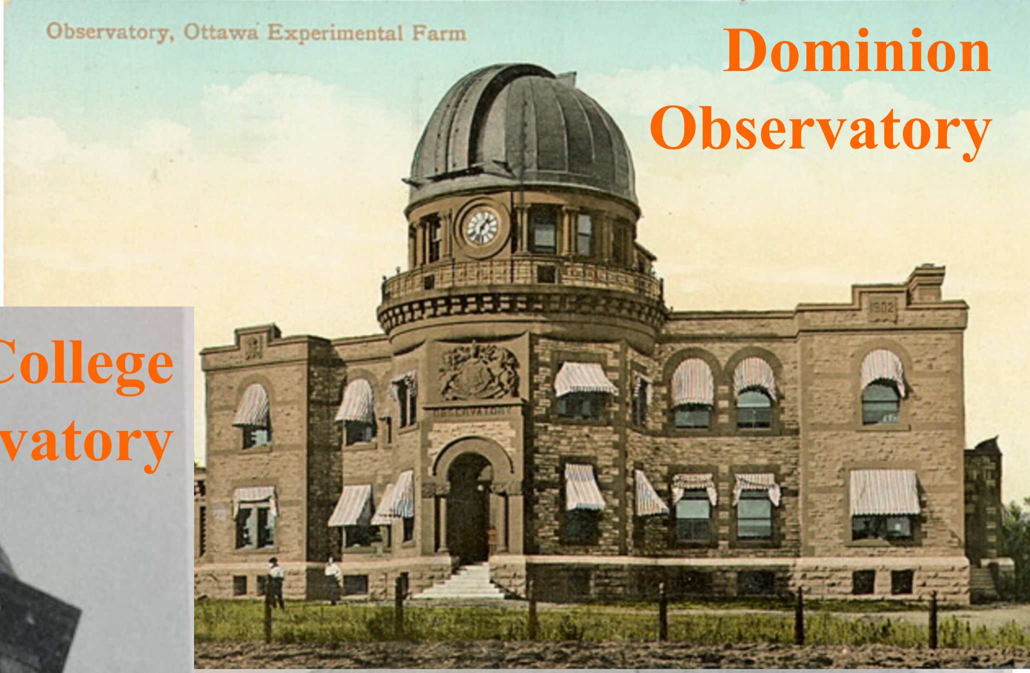
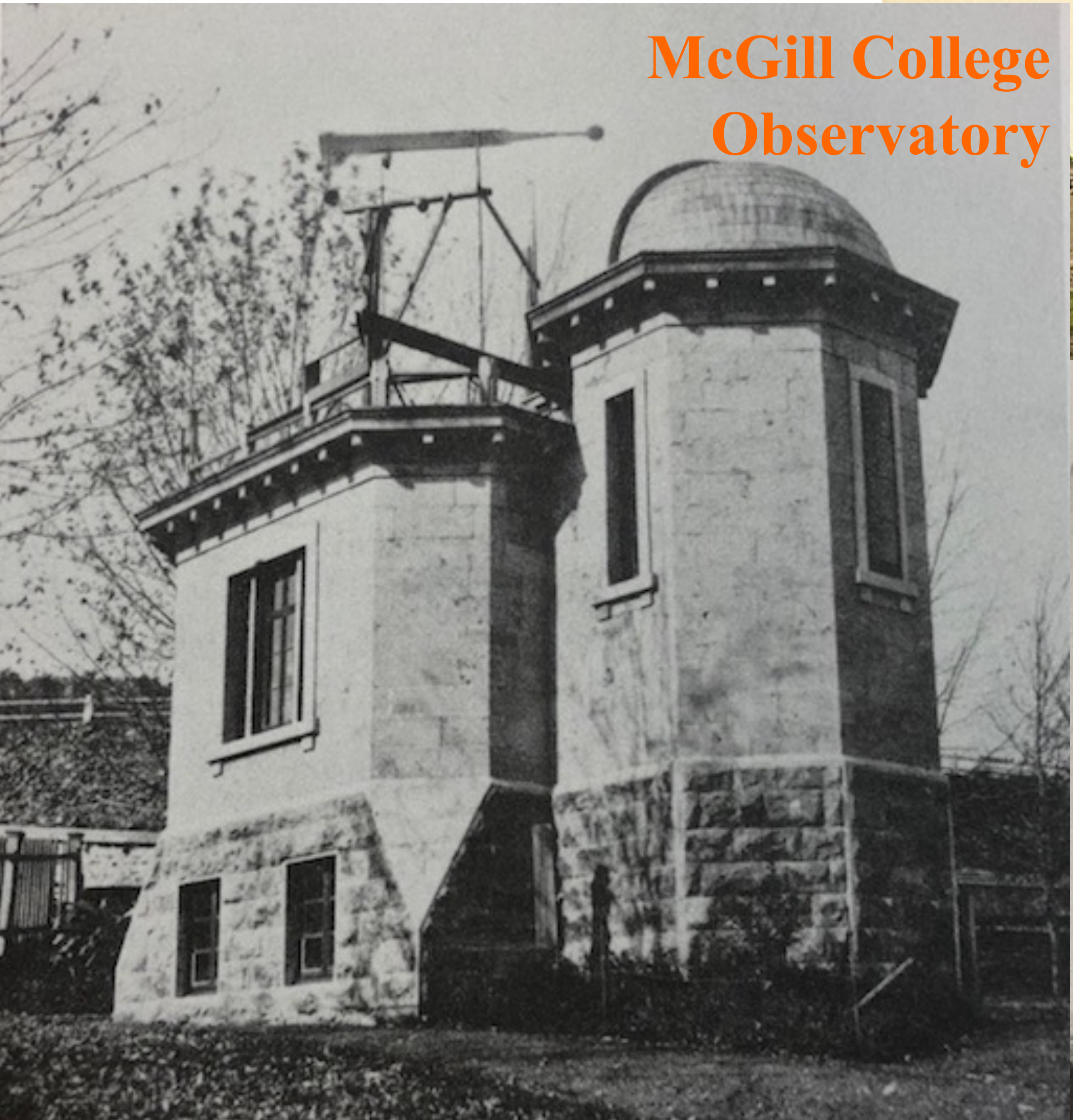
THE
HEAVENS ABOVE
AND
THE EARTH BENEATH
A History of the Dominion Observatories
OBSERVATORY
Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada
Canada

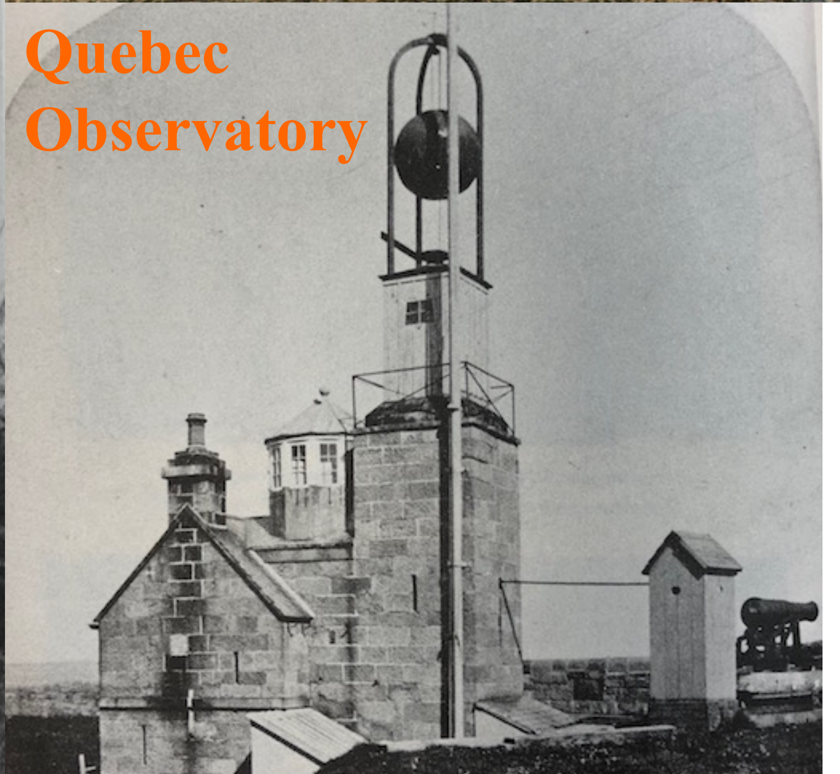

Yukon Territory
Northwest Territories
Nunavut
British Columbia
Alberta
Saskatchewan
Manitoba
Ontario
Quebec
Newfoundland and Labrador
New Brunswick
P.E.I.
Nova Scotia

Keeping Time

*"Now, the National Research Council time signal.
The beginning of the long dash following ten seconds of silence indicates exactly one o'clock, Eastern Standard Time."*





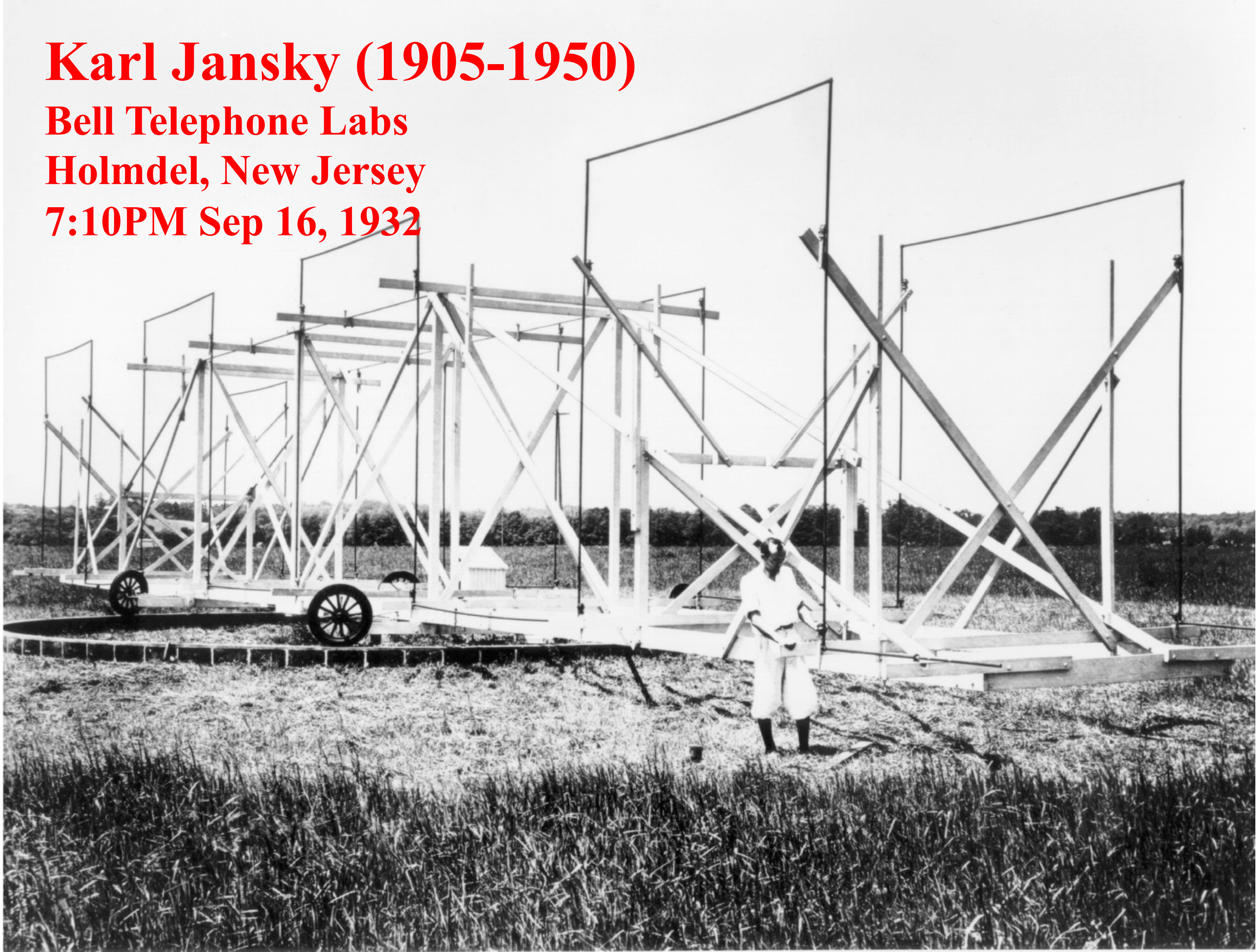


1918: Plaskett Telescope Opens at Dominion Astrophysical Observatory in Victoria

John Stanley Plaskett
(1865-1941)

Karl Jansky (1905-1950)

Bell Telephone Labs
Holmdel, New Jersey
7:10PM Sep 16, 1932



New York Times
May 5, 1933

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International

Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

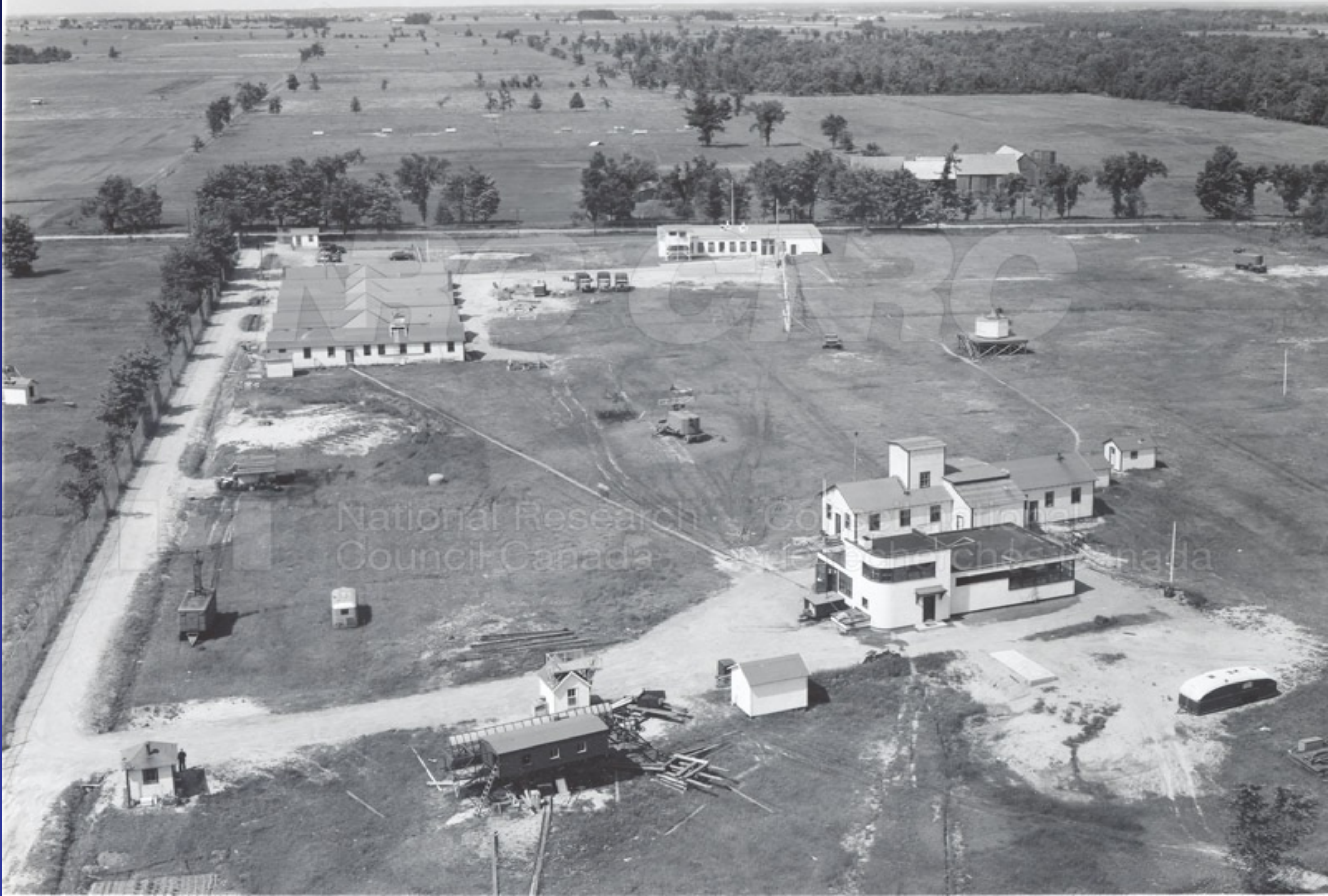
If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days

NRC Radio Field Station in Ottawa, 1943



Canada's First Radio Telescope (48")

FIG. 2
10.7-CENTIMETER RADIOTELESCOPE
FRONT VIEW

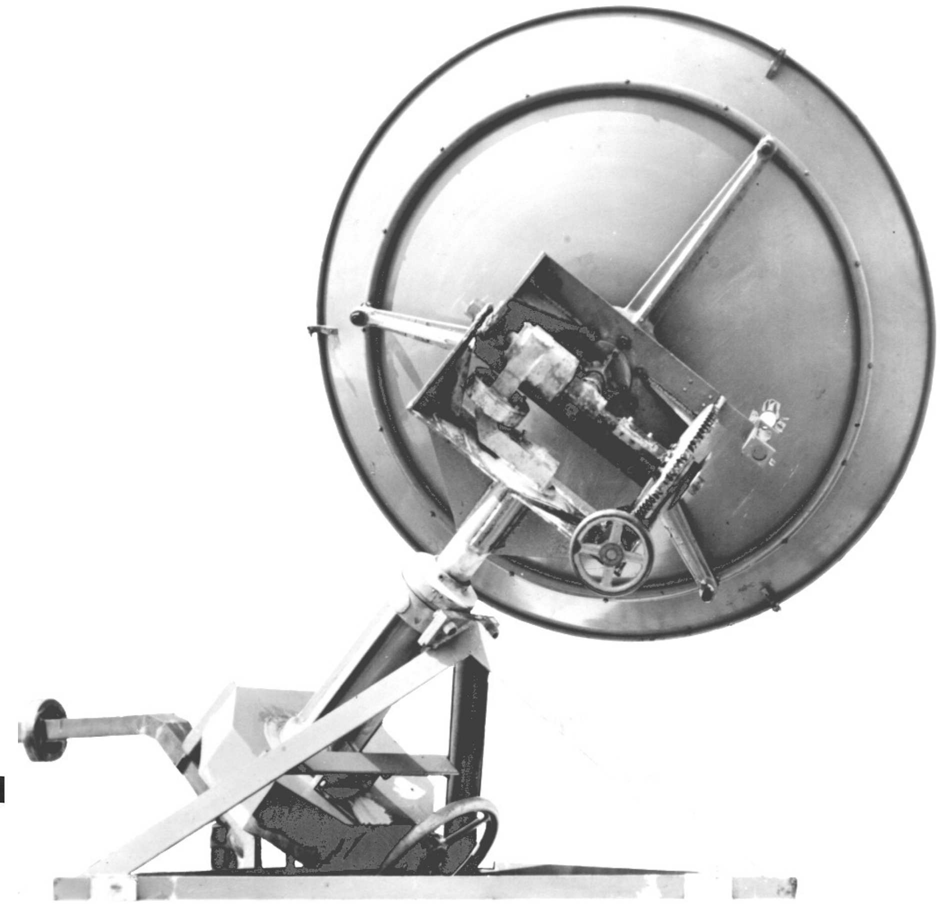
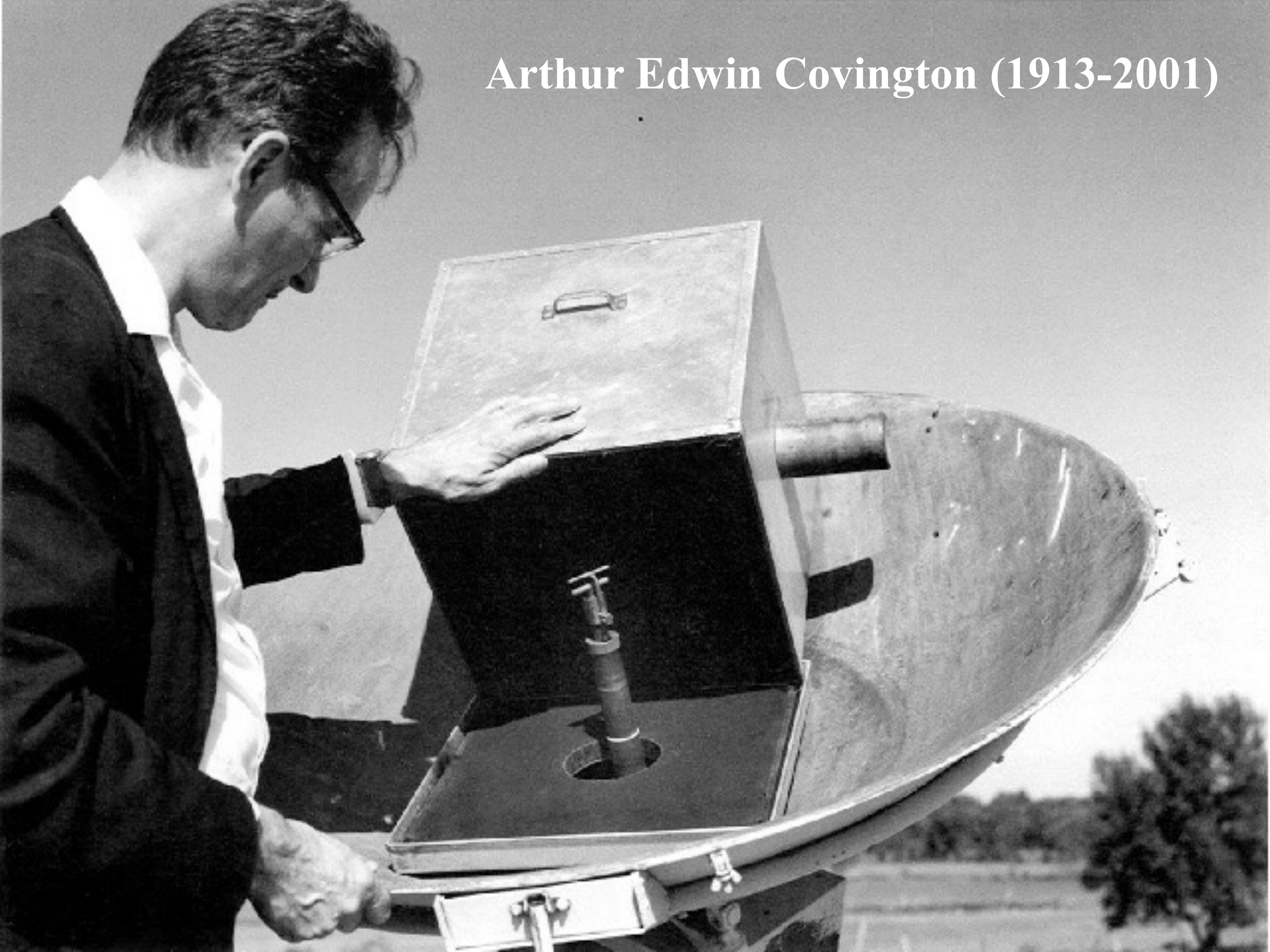


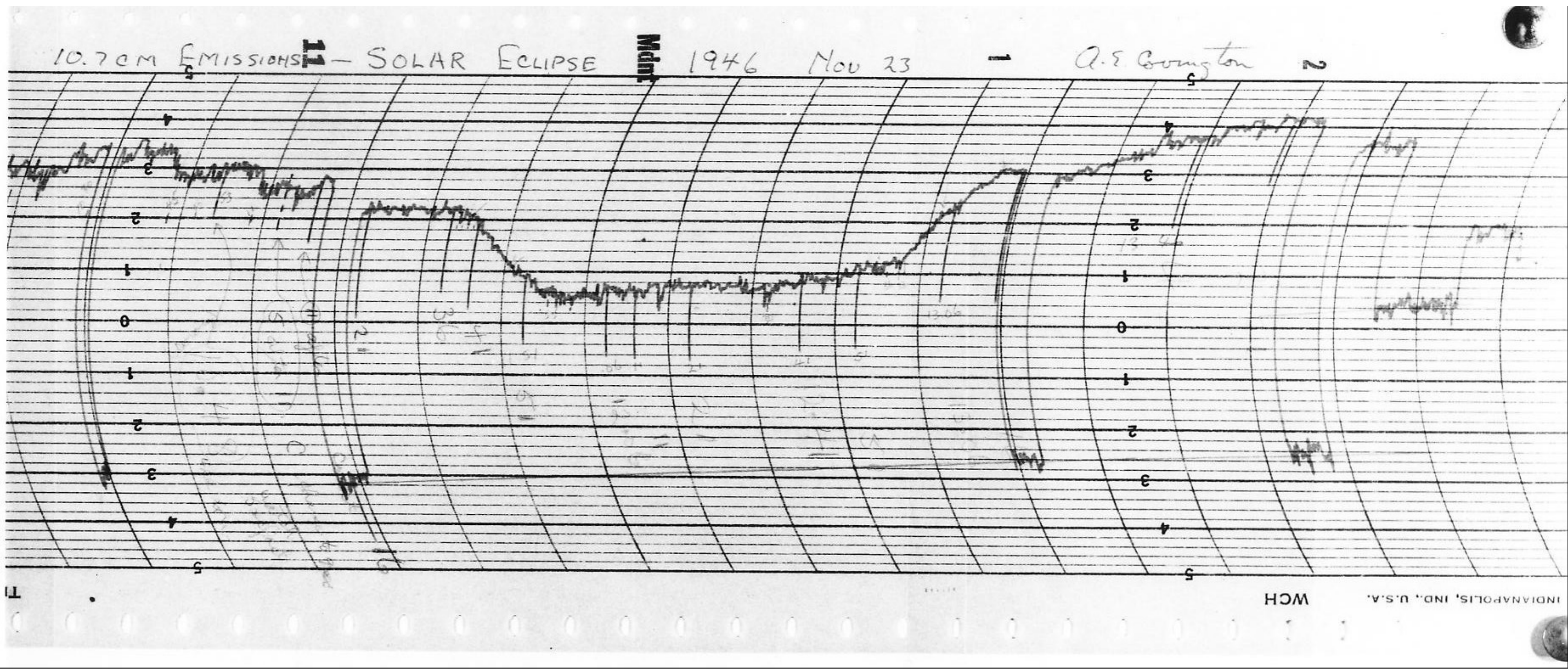
FIG. 3
10.7-CENTIMETER RADIOTELESCOPE
REAR VIEW

First observation of the Sun: 26 July 1946



Arthur Edwin Covington (1913-2001)

Solar Eclipse: 23 November 1946



1.5 million K sunspot

Peter M. Millman (1906-1990)

&

Donald R. W. McKinley (1912-1984)

NRC Springhill Meteor Observatory

ground reflector mats for radar antennas

PLATE I

Springhill Meteor Observatory from the air. Main building, with photographic observing station on the roof, appears to upper right of center. Visual observing station is in far upper right. Transmitting and receiving aerials for IGY meteor system appear in the foreground and left background, respectively.

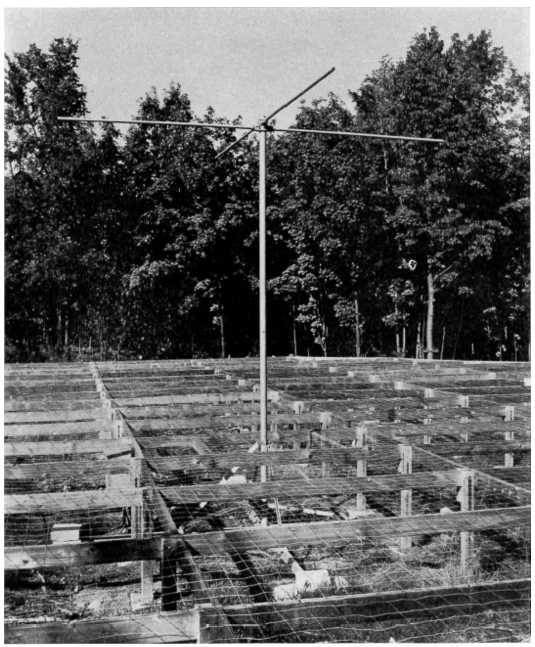
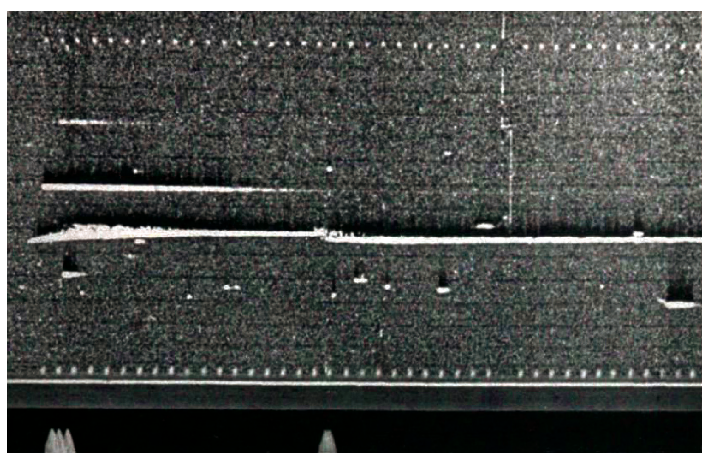
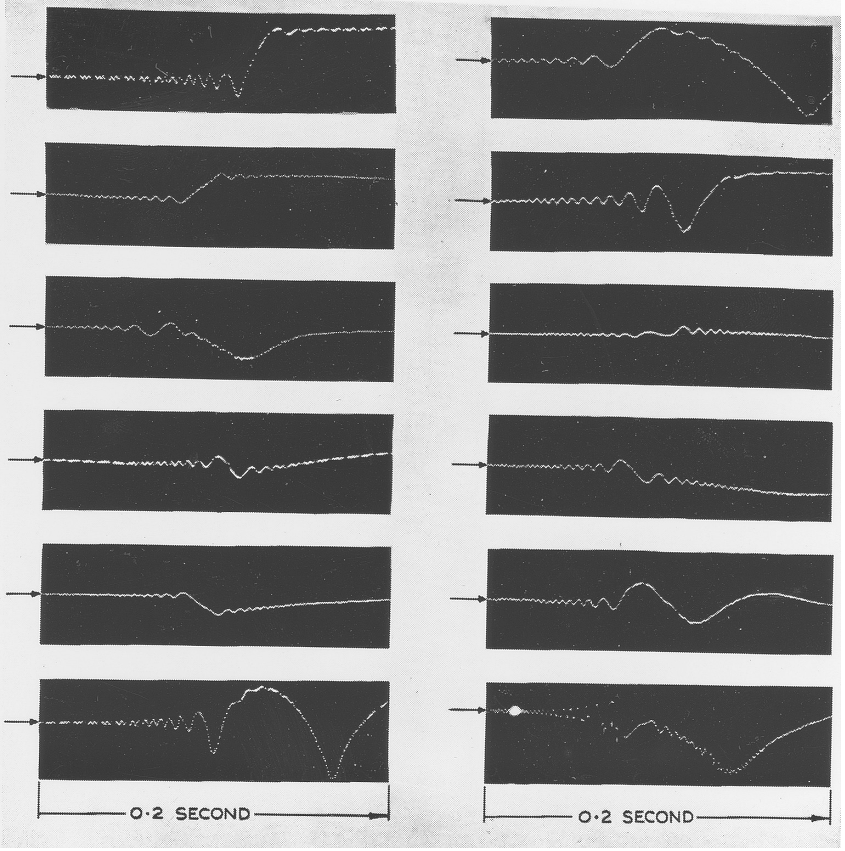


PLATE VII

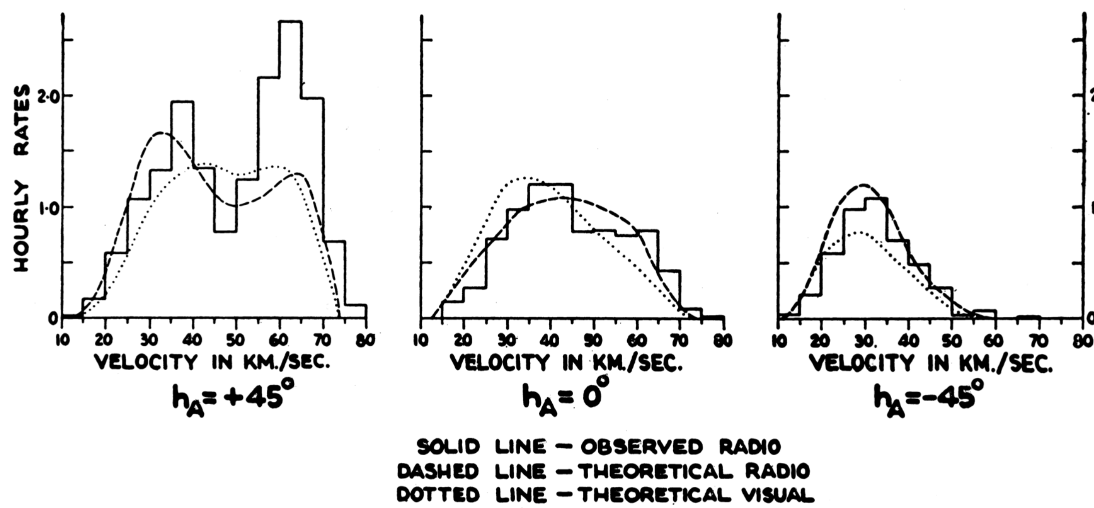
33 mc/s antenna for 20 kw meteor radar



Delta Aquarid 1948
July 29



Meteor Echoes
= “Doppler Whistlers”



<u>No</u> interstellar meteors

McKinley (1951)

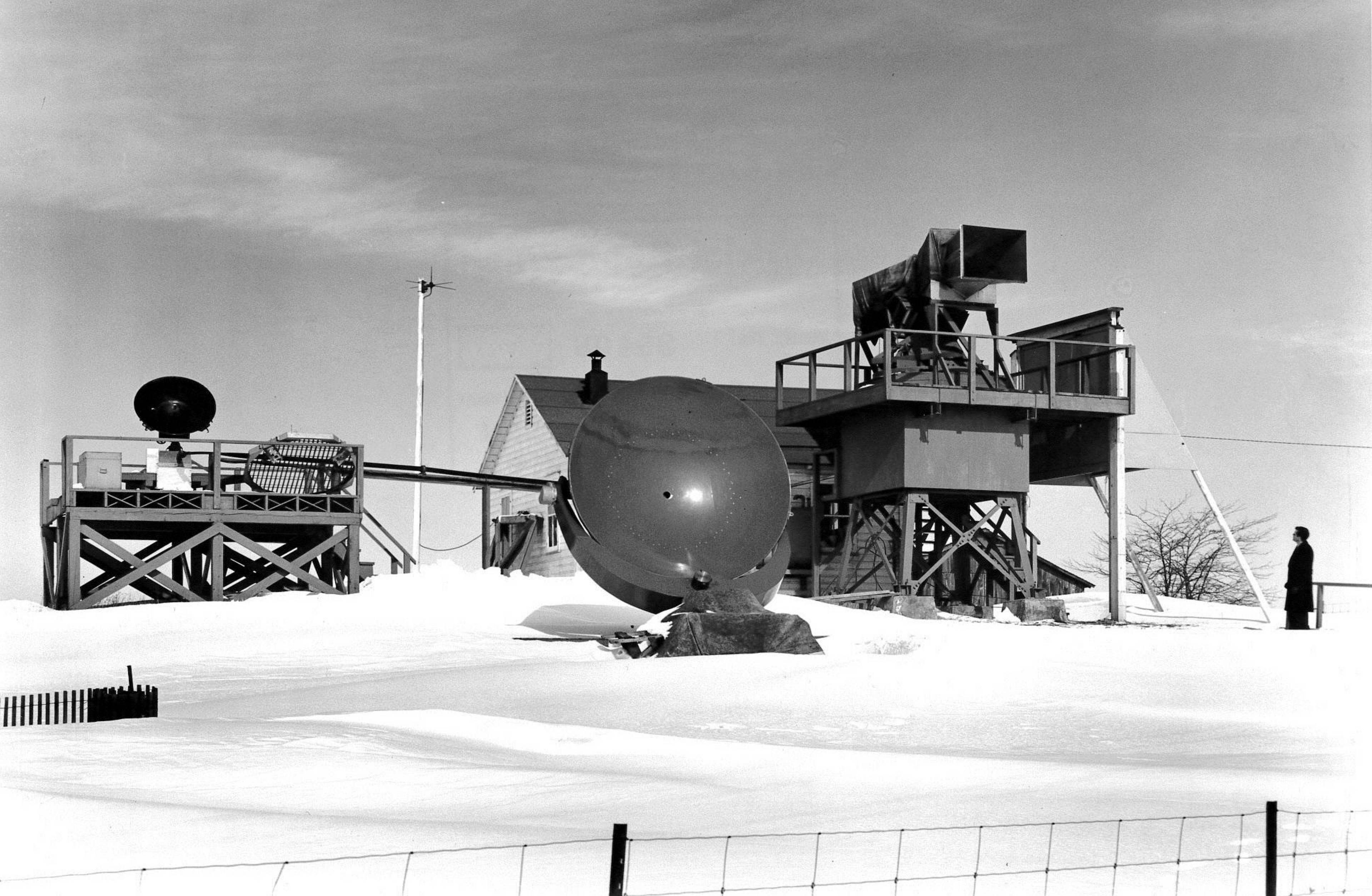
22 June 1949:

The American Astronomical Society meets in Ottawa.

Grote Reber (1911-2002) visits the 10.7-cm radiometer at the Goth Hill Solar Noise Observatory.

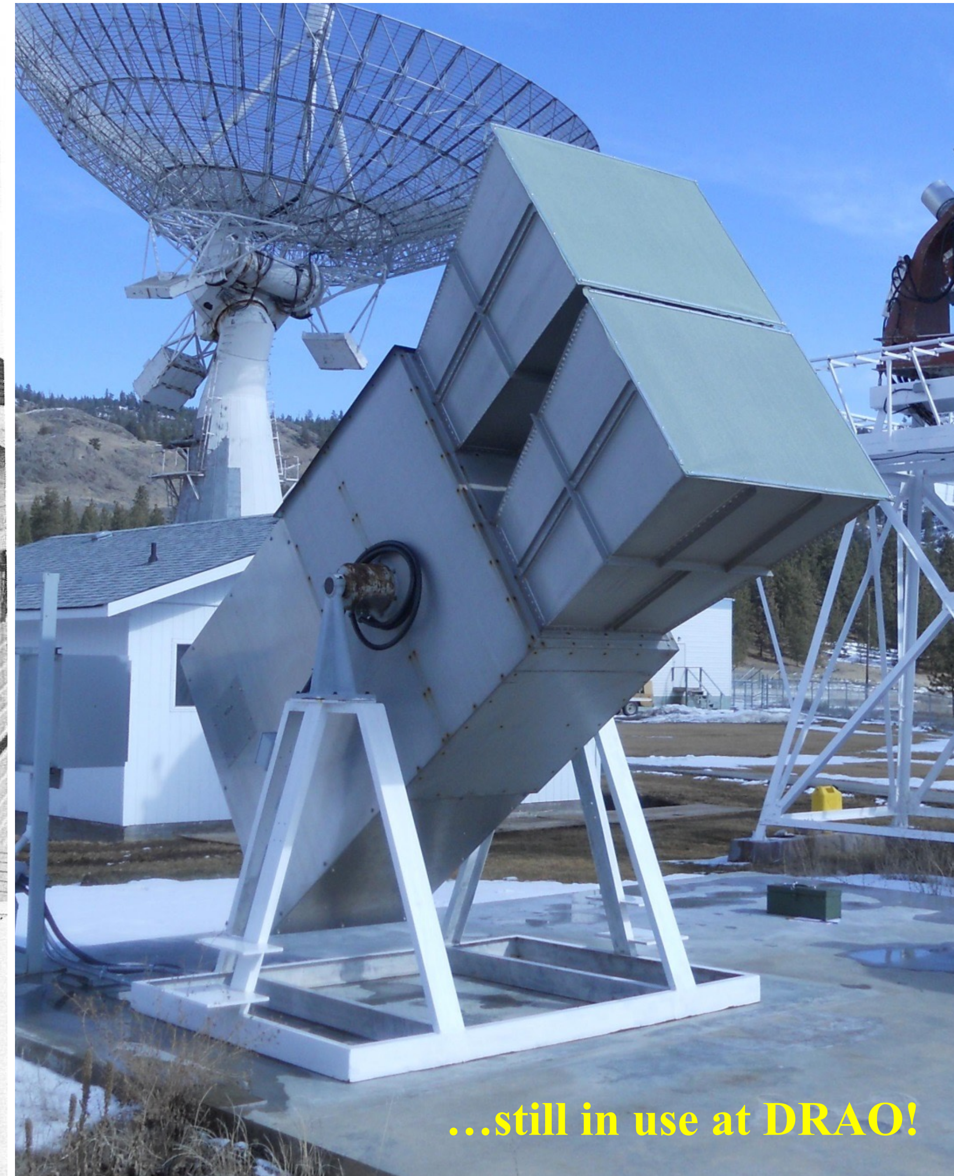
Photo Credit: Grote Reber

Goth Hill Observatory in Ottawa



Norm Broten (1921-2015) and the Goth Hill 10-ft Dish

Calibration Horn Antenna



…operated until 1970.

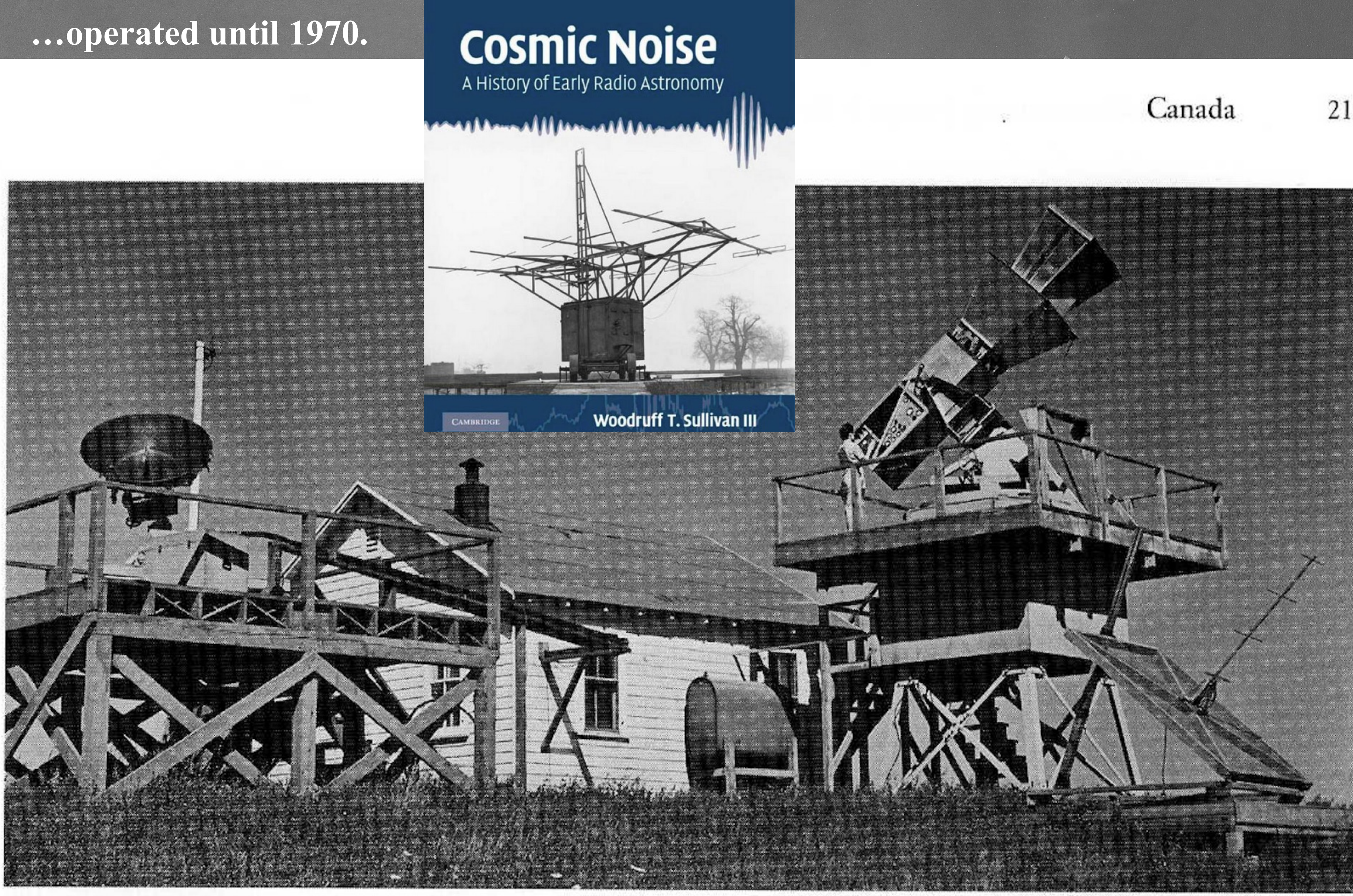
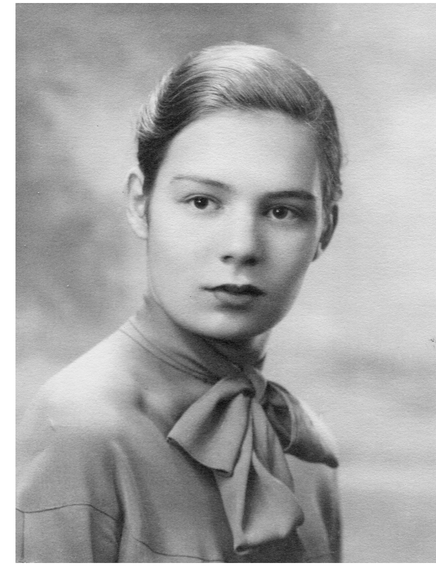


Figure 10.7 Arthur Covington's field station (1950) at Goth Hill, south of Ottawa. Left to right are a 4 ft dish (10.7 cm wavelength), Covington standing at a wideband (10–30 cm) receiver and horn, and a Yagi (1.5 m) for monitoring solar bursts.

GOTH HILL SOLAR NOISE OBSERVATORY

…operated until 1970.

Gladys A. Harvey (1916-1995)

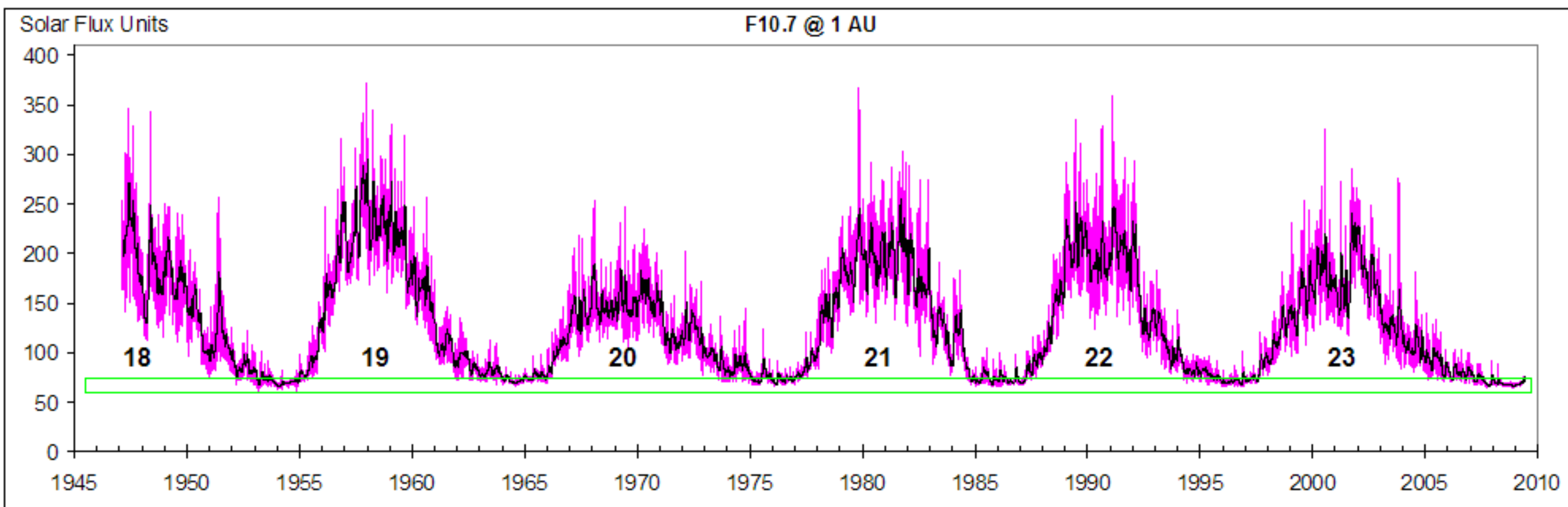


- The First Canadian Woman Radio Astronomer
- 1937 BA Math & Physics at McMaster
- 1938 MA Math at McMaster
- Worked at NRC Radio and Elec. Eng. Division in Ottawa.
- Started at Goth Hill in March 1948.
- Member of NRC Solar Patrol for 20 years.
- Wrote sole-author Astrophysical Journal paper correlating radio bursts to solar flares in 1964.

Photo Credits: Heather Harvey

10.7-cm Solar Flux Monitoring Program

- Started Feb. 1947 in Ottawa.
- Moved to ARO and DRAO in early 1960s.
- Continues today at DRAO…

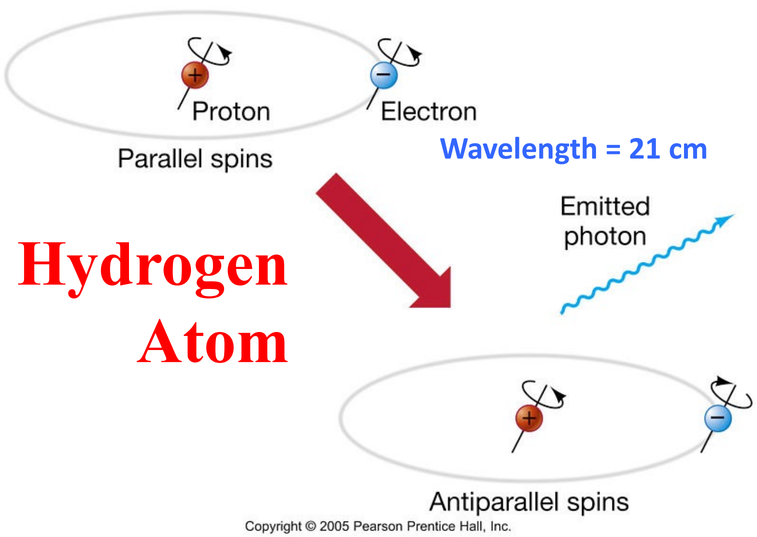


The 21-cm Line

1945:

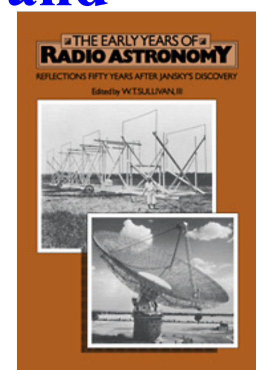
Henk van de Hulst predicts atomic hydrogen in space should emit radio waves at 1420.4058 MHz, or 21 cm.

Hydrogen Atom



Hendrick C. van de Hulst (1918-2000)

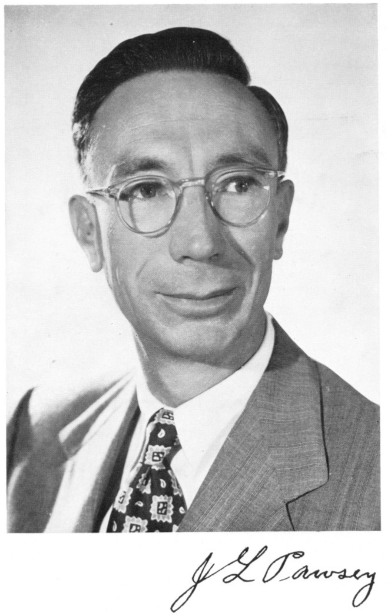
"Early visitors to the Radio Field Station and to Goth Hill whom I can recall… were"----- Appleton, Hey, Ratcliffe, Bolton, Friis, Pawsey and van de Hulst. "I was introduced to Pawsey during one of his early visits to the RFS by W.J. Henderson; they attended Cambridge at the same time…" When Pawsey saw the 10-30 cm horn in 1948 (for absolute flux determination), "he told me about the 21 cm hydrogen line prediction and wondered whether I could make … any observations for its confirmation. As it stood, the instrumentation was hardly suitable. This was the first time that I had heard of the prediction and is one occasion when I realized the magnitude of the difficulties of switching from one promising area to another. I readily gave a negative reply and realized that I would be continuing solar noise work…"



Arthur Covington

in Woody Sullivan's *The Early Years of Radio Astronomy*

Joe Pawsey: Founder of Australian Radio Astronomy

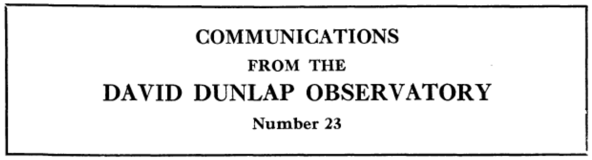


- **Married Canadian Lenore Nicoll in 1935.**
- **Three visits to NRC in Ottawa:**
  - **1941**
  - **1947, meets Arthur Covington…**
    - ***"At Ottawa, Covington is a young and inexperienced man working in relative isolation. He has got some thoroughly useful results by good honest work and perseverance."***
  - **1957, met with Don McKinley, Peter Millman, C.S. Beals, Norm Broten, and talked with Jack Locke about plans for DRAO.**

200 MHz sea-cliff interferometer at Dover Heights, Sydney

Ralph E. Williamson (1917-1982)

David Dunlap Observatory,
Richmond Hill, Ontario,
December 21, 1949.



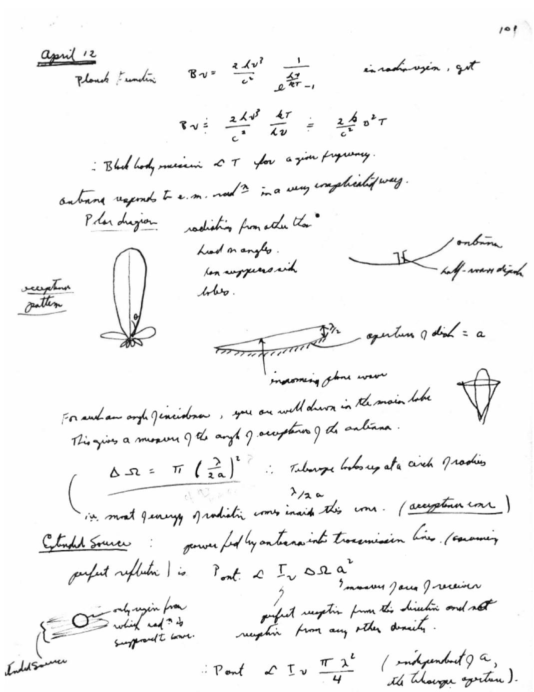
COMMUNICATIONS
FROM THE
DAVID DUNLAP OBSERVATORY
Number 23

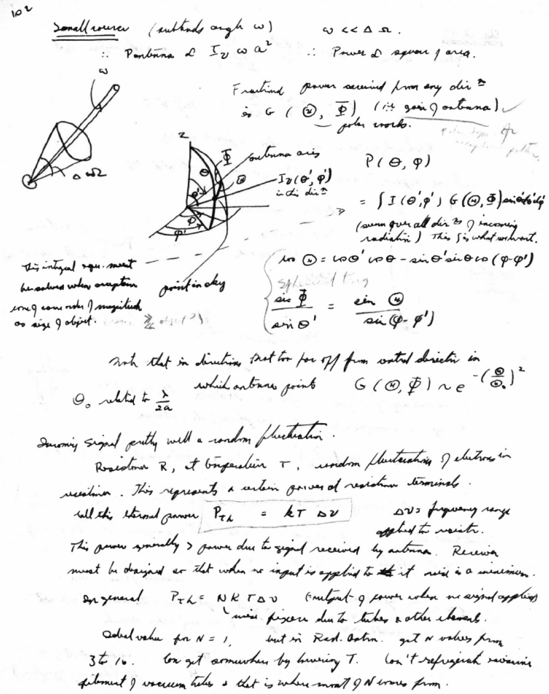
CONCERNING THE SOURCE OF GALACTIC RADIO NOISE

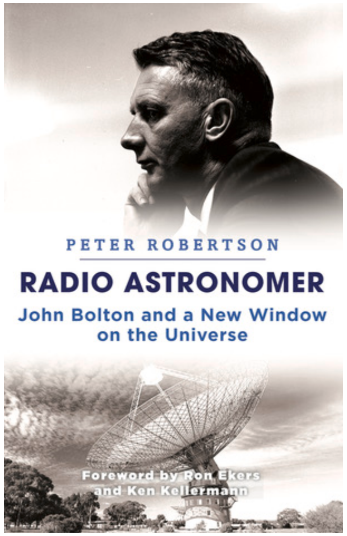
BY RALPH E. WILLIAMSON

ALTHOUGH the existence of radio-frequency radiation from the galaxy has been recognized for more than fifteen years, and considerable observational work has been done in surveying the distribution of this "galactic noise" with respect to direction in various frequencies, no completely satisfactory explanation for its cause has yet been advanced. The only hypothesis sufficiently definite to be susceptible of an observational test is that first advanced by Reber[1], and then by Henyey and Keenan[2], which attributes the galactic noise to emission from the so-called free-free transitions of electrons in the field of protons in interstellar space.

U of T Notes taken by Vic Gaizauskas from Williamson's April 1951 Lectures on Radio Astronomy







John Bolton (1922-1993) from CSIRO in Australia gave seminar at U of T on radio astronomy in November 1950.

Jack Locke (1921-2010)

1956: Jack Locke arranges a 6-part colloquium series at Dominion Observatory in Ottawa on radio astronomy.

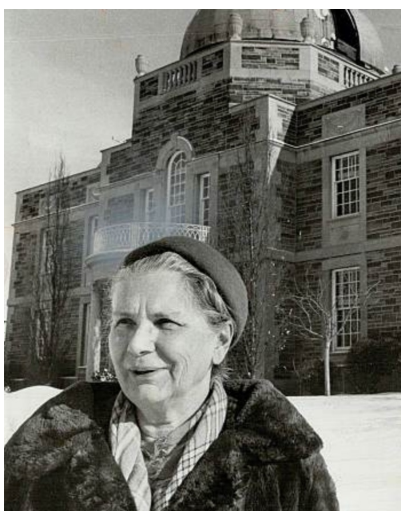
C.S. Beals (1899-1979)

John Bolton (1922-1993)

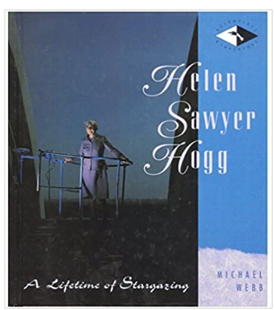
Dominion Astronomer C.S. Beals invites Bolton (now at Caltech) to Ottawa to give a colloquium on radio astronomy.

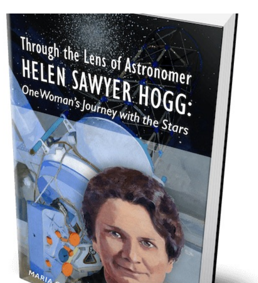
65 Years Ago

"In the summer of 1956, when Helen Hogg came through Ottawa, a meeting was called with McKinley, Beals, Harrison (in place of Parsons), and myself to discuss the future of Canadian radio astronomy."

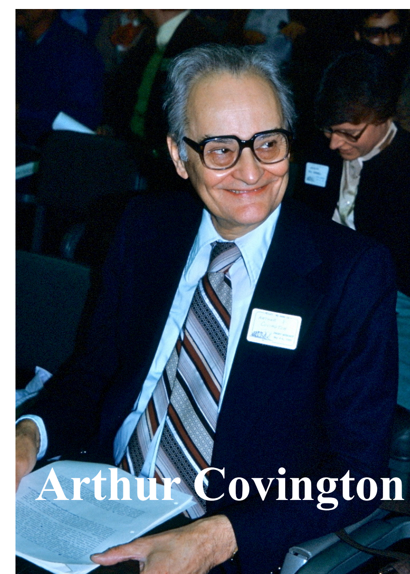


Helen Sawyer Hogg (1905-1993)





Arthur Covington
1990 Interview
with
Richard Jarrell



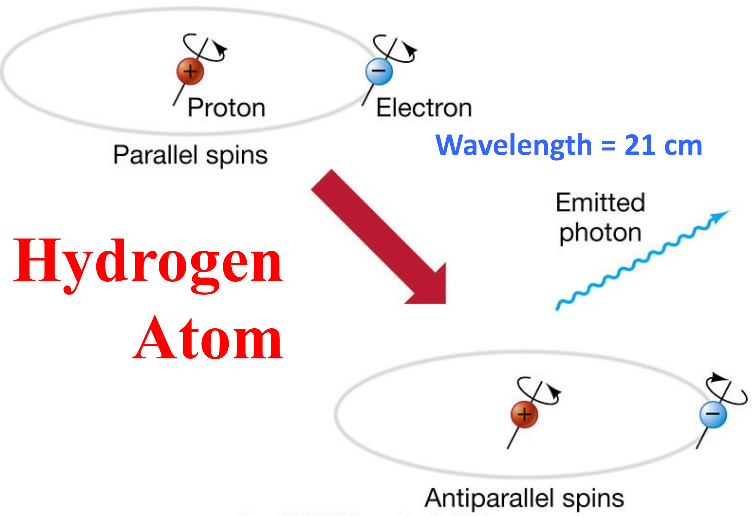
The 21-cm Line

1945:

Henk van de Hulst predicts atomic hydrogen in space should emit radio waves at 1420.4058 MHz, or 21 cm.

Six years pass with no discovery.

Hydrogen Atom



Hendrick C. van de Hulst (1918-2000)

The 21-cm Line

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Six years pass with no discovery.

March 25, 1951:
Harold "Doc" Ewen &
Edward Purcell
(1952 Nobel Prize for NMR)
…measure the 21-cm line using a horn antenna sticking out of window of Lyman Hall at Harvard.

April 28, 1956
Harvard, Massachusetts

TECHNICAL SURVEYS
CENTRAL REGISTRY
PAPER NO 502 REC'D. MAY. 1 '56
FILE NO.
REFER TO

Dr. G.S. Hume,
Acting Deputy Minister.

April 30, 1956.

Recent trips to American Astronomical Society, March 22-24;
Inauguration Ceremonies, Harvard 60 Foot Radio Telescope, April 28, 1956.

The major reason for two recent trips made by myself to scientific meetings or institutions (American Astronomical Society, March 22-24 - Inauguration Ceremonies, Harvard 60 ft. radio telescope, April 28, 1956) has been to gather information on radio astronomy and its possible future use by our Branch.

Radio astronomy as an active branch of science has arisen from the discovery that, in addition to visual and photographic light, the sun, the stars, the planets, the gas clouds of the galaxy and the external galaxies all emit radiation of the order of centimeters or meters in wavelength. This relatively long wave-length radiation is electromagnetic radiation similar in its fundamental aspects to ordinary light and with suitable receiving equipment may be used to gain astronomical information about the positions, motions and physical characteristics of the heavenly bodies.

At the meeting of the American Astronomical Society at Columbus, Ohio, March 22-24 the most important single subject was radio astronomy. Numerous papers were presented dealing with planetary, stellar and galactic radiation and a symposium was held dealing with instrumental problems and the interpretation of radio observations of both near and distant astronomical bodies.

The official opening of the new Harvard 60 ft. radio telescope on April 28 offered similar opportunities for studying the present position. A day of meetings were held and there were numerous opportunities for personal discussions with successful research workers in this field. In addition to these two meetings a series of six colloquia organized by Dr. J.L. Locke and devoted to the subject of Radio Astronomy has been held at the Dominion Observatory and attended by most of the scientists of the Ottawa area interested in this subject.

Without attempting to review the entire field it would appear for the type of astronomical studies occupying our major interest at Victoria, and to some extent at Ottawa namely galactic studies, that the introduction of radio techniques is very closely analogous to the revolution introduced into the practice of medicine by the use of X rays. Ordinary photographic and visual light is absorbed by the dust particles pervading the galaxy to such an extent that only a volume of space approximately 2,000 parsecs in diameter can be effectively examined. Making use of the long wavelength radiation (21 cm) produced by clouds of neutral hydrogen and presumably other atoms and molecules it is possible to penetrate to a distance 10 times as great.

While this does not make conventional astronomy obsolete any more than the introduction of X rays outmoded the direct use of the human eye, nevertheless it does place at a great disadvantage any major astronomical organization which does not have these techniques available.

Dr. G.S. Hume,
Acting Deputy Minister.

April 30, 1956.

Recent trips to American Astronomical Society, March 22-24;
Inauguration Ceremonies, Harvard 60 Foot Radio Telescope, April 28, 1956.

We are considering the impact of these new discoveries on the work of our Branch and will no doubt be discussing it with you in greater detail in the future. There are, however, one or two remarks I should like to make in the hope of getting your reaction to them.

1. It would appear that this is a period in history when it is neither safe nor politic for a country like ours to fall behind others in scientific development.

2. The continued progress of radio astronomy now seems inevitable and if the well qualified astronomers of our Branch do not take it up it will be done by others (e.g. the Electrical Engineering Branch of N.R.C.) at equal or greater cost to the country and lesser profit to astronomy.

3. While we are definitely behind other modern countries in this fast growing branch of science this is less of a disadvantage than it might appear. An effort began five years ago would almost certainly have loaded us up with inadequate and obsolete equipment. By starting now when many of the technical problems have been solved we may well be further ahead in the long run. We propose to spend the next few months in active study of instruments, techniques and costs in order to be able to place definite proposals before the Department.

C. S. Beals

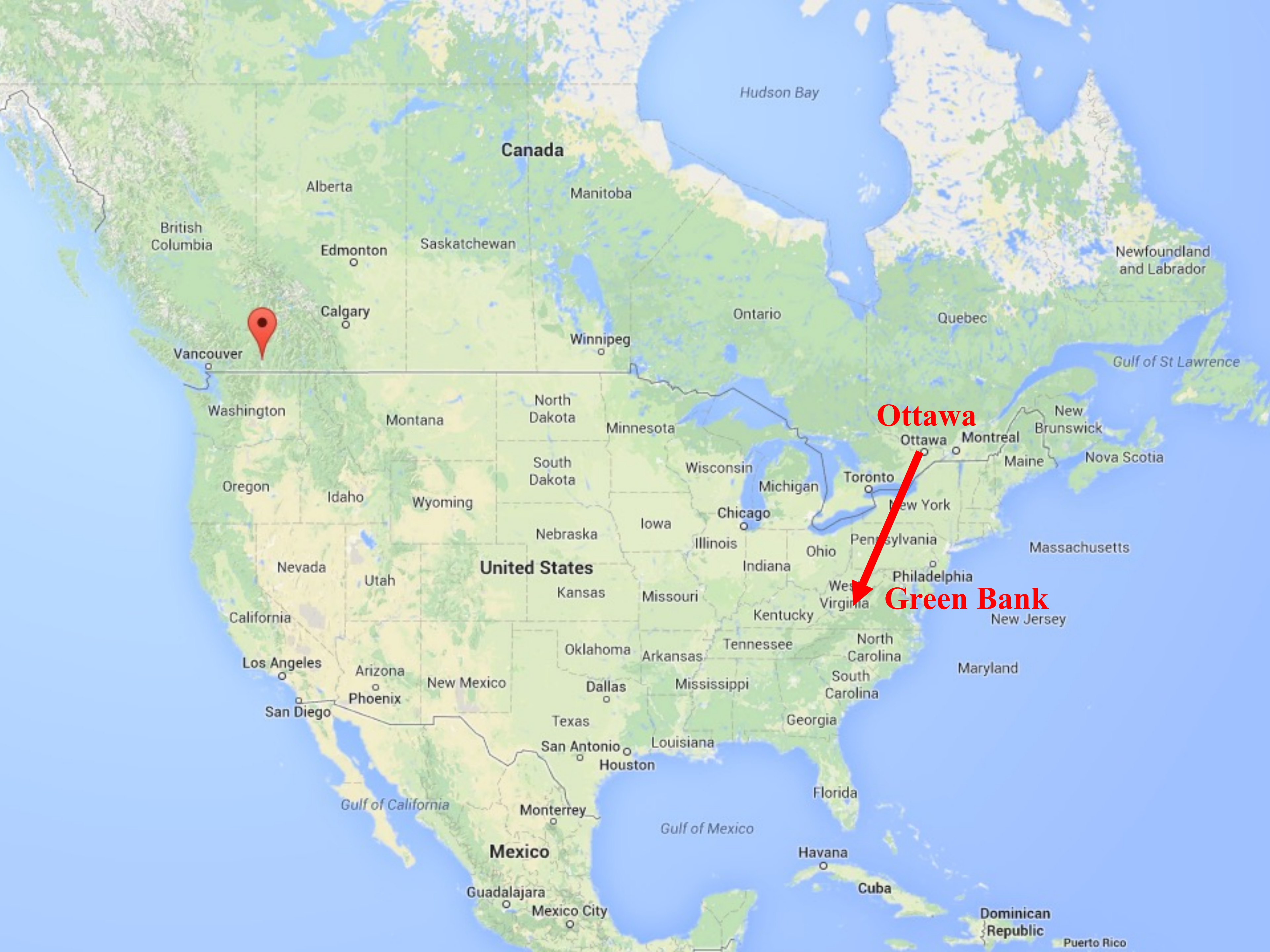
C.S. Beals,
Dominion Astronomer

Carlyle Smith Beals
(1899-1979)

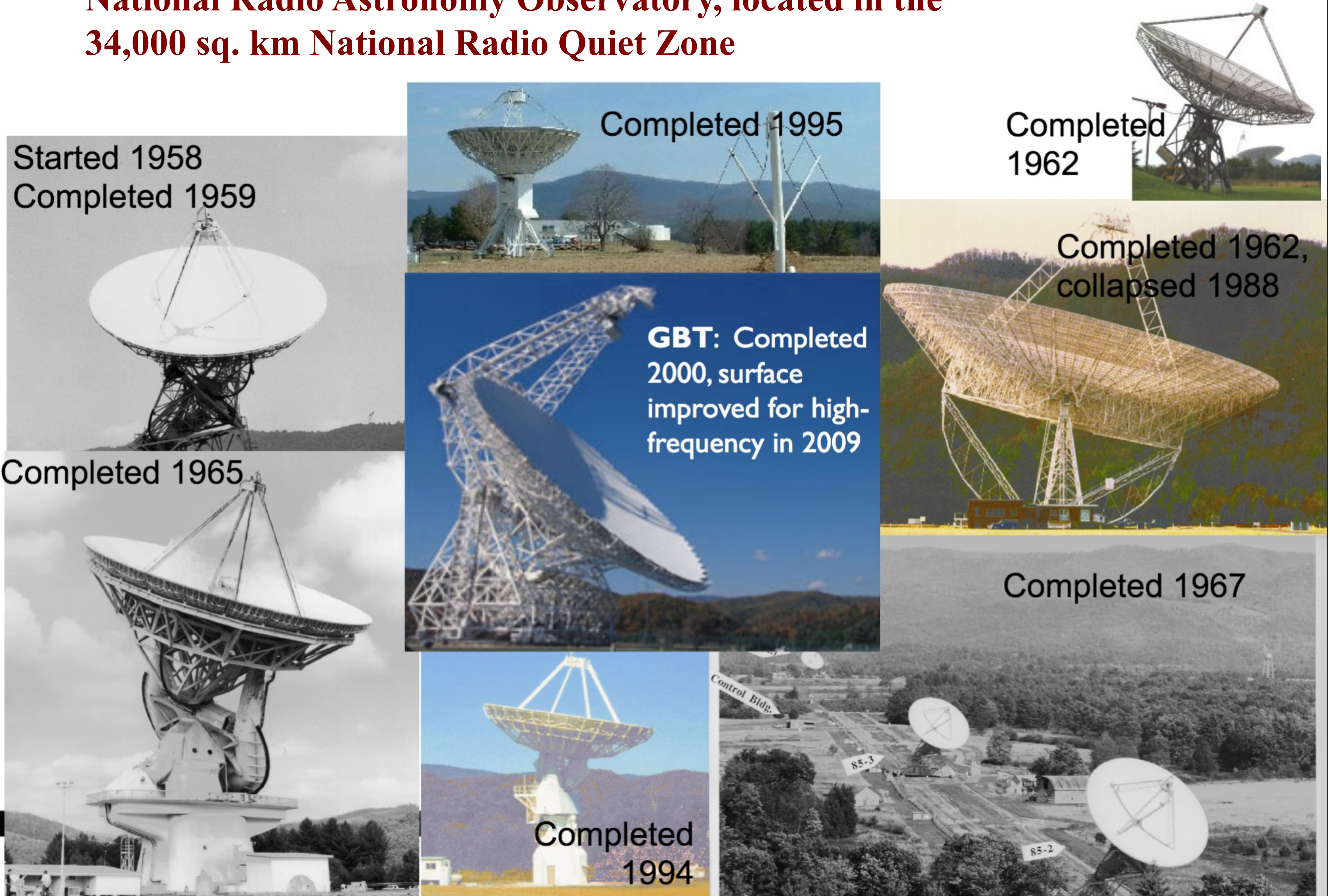
Where Should DRAO Be Built?

In March of 1957 Ed Argyle and I set out from Ottawa in a Travelall, with some field intensity measuring equipment which we had gathered together, to test a number of preselected sites in British Columbia. We went by way of Greenbank and Owens Valley, the purpose being to use the measured interference levels at these sites as a basis of comparison. We first visited White Lake in early June and found it to be the best of all the sites we had visited, both in terms of interference and in convenience. At the end of June we were joined by Nick Pattenson and George Aitken from NRC who made additional interference measurements and propagation tests in the 950 to 4000 MHz range. (Our own measurements were restricted to the 55 to 950 MHz range.) The NRC results confirmed the excellence of the site and a final decision to locate at White Lake was made following Dr. Beals's visit to the site in mid-July.

Jack Locke (1921-2010)
1st Officer in Charge


Ottawa
Green Bank
Hudson Bay
Canada
Alberta
Manitoba
British Columbia
Edmonton
Saskatchewan
Newfoundland and Labrador
Calgary
Ontario
Quebec
Vancouver
Winnipeg
Gulf of St Lawrence
Washington
North Dakota
Montana
Minnesota
New Brunswick
Ottawa
Montreal
Maine
Nova Scotia
South Dakota
Wisconsin
Oregon
Idaho
Wyoming
Michigan
Toronto
Chicago
Iowa
Nebraska
Illinois
Ohio
Massachusetts
Nevada
Utah
United States
Indiana
Philadelphia
Kansas
Missouri
California
Kentucky
New Jersey
Tennessee
North Carolina
Oklahoma
Arkansas
Maryland
Los Angeles
Arizona
New Mexico
Dallas
Mississippi
South Carolina
Phoenix
San Diego
Texas
Georgia
San Antonio
Louisiana
Houston
Florida
Gulf of California
Monterrey
Gulf of Mexico
Mexico
Havana
Cuba
Guadalajara
Mexico City
Dominican Republic
Puerto Rico

Green Bank, West Virginia, is the original site of the U.S. National Radio Astronomy Observatory, located in the 34,000 sq. km National Radio Quiet Zone



March 1957 Site Testing

March 1957 Site Testing


Penticton
Vancouver Island
Ottawa
Green Bank
Owens Valley
Hudson Bay
Canada
Alberta
Manitoba
British Columbia
Edmonton
Saskatchewan
Calgary
Ontario
Quebec
Newfoundland and Labrador
Winnipeg
Gulf of St Lawrence
Washington
Montana
North Dakota
Minnesota
New Brunswick
Montreal
Maine
Nova Scotia
South Dakota
Wisconsin
Michigan
Toronto
Oregon
Idaho
Wyoming
Chicago
Iowa
Nebraska
Illinois
Ohio
Pennsylvania
Massachusetts
Nevada
Utah
United States
Indiana
Philadelphia
Kansas
Missouri
New Jersey
Oklahoma
Arkansas
Tennessee
North Carolina
Maryland
New Mexico
Dallas
Mississippi
South Carolina
Texas
Georgia
San Antonio
Louisiana
Houston
Florida
Monterrey
Gulf of Mexico
Havana
Mexico
Cuba
Guadalajara
Mexico City
Dominican Republic
Puerto Rico
Owens Valley Radio Observatory
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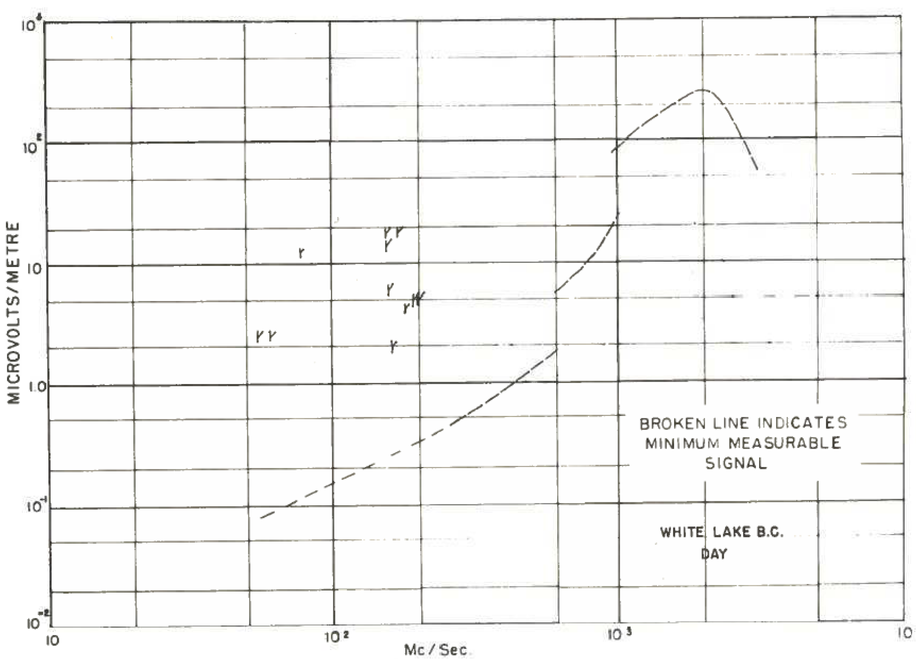
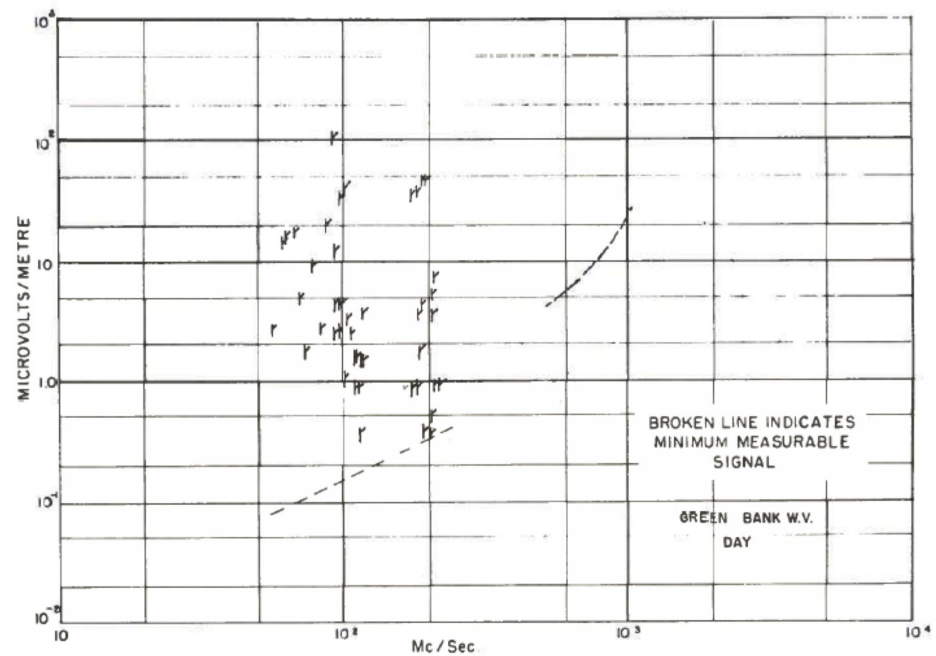
Jay M. Pasachoff

June 1957 Site Testing

Locke and Argyle, during April and May, measured radio noise intensities in the 50 to 1000 mc/s band at two of the American sites: Greenbank, W.V., and Big Pine, Cal., so that comparison might be made between Canadian and American sites. Following this, they made preliminary measurements at several sites in British Columbia. During July and August, the combined NRC/Observatory group completed measurements at three of the most promising British Columbia sites and on the basis of these measurements, chose a site near Penticton as being the most suitable for the Dominion Observatory telescope. Subsequent to the loca-





PROBLEM:

The Dominion Observatory doesn't have a radio astronomer to become director of DRAO!

SOLUTION:

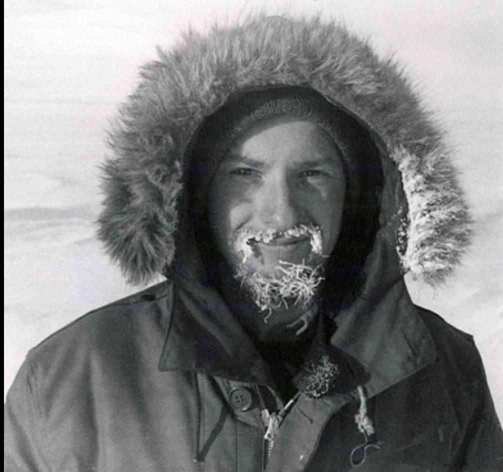
Make one!


John Galt
1944-1945
Royal Canadian Navy Volunteer Reserve
Signal Corps Training as Radio Artificer
(War ended, never sent abroad.)

1945-1949: University of Toronto (Physics)
Summer 1948: Night assistant at David Dunlap Observatory


CANADA
DEPT OF MINES AND RESOURCES
DOMINION OBSERVATORY
MAGNETIC STATION

August



A photographic record of the year I spent in the Arctic operating the Dominion Observatory's Magnetic Station at Resolute Bay on Cornwallis Island.

John Galt.

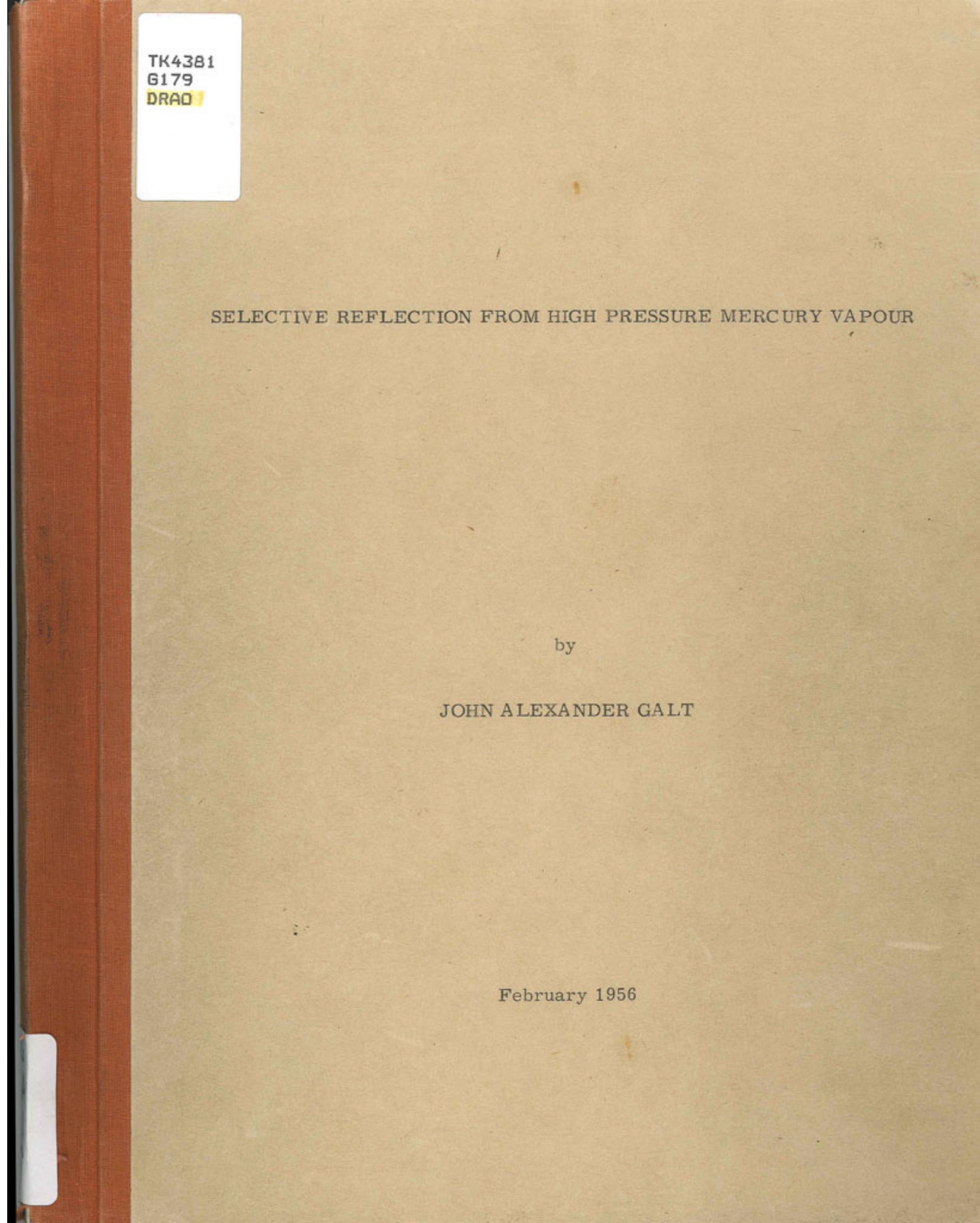
1949-1950

Midnight sun near end of summer.

1950-1956
University of Toronto
PhD Physics

Summer 1952
Summer student at Dominion Astrophysical Observatory
Built photometer for Plaskett telescope with Ed Argyle

Summer 1954
Summer student at Dominion Astrophysical Observatory
June 29th solar eclipse expedition to Hansen, ONT "clouded out"



SELECTIVE REFLECTION FROM HIGH PRESSURE MERCURY VAPOUR

by

JOHN ALEXANDER GALT

February 1956

DUPONT®

1956-1957

The miracles of science™

- **Worked at Dupont for a year.**
- **Missed research and didn’t like the company.**
- **Applied to Leiden, Cambridge, and Jodrell Bank as a post-doctorate fellow.**
- **Lovell said, yes, you can come to Jodrell... but we’re not sure about the money.**
- **Applied for Dominion Observatory radio astronomer position, was interviewed by Beals and Locke.**
- **Was offered the position, but observatory wasn’t ready, so Dominion paid for John’s "postdoc" at Jodrell Bank where he was to learn the ropes of radio astronomy before returning to Canada to be the first director of DRAO.**

1958: Jodrell Bank 250-ft Telescope

Bolton & Wild 1957
ApJ, 125, 256


John G. Bolton (1922-1993)


J. Paul Wild (1923-2008)

ON THE POSSIBILITY OF MEASURING INTERSTELLAR MAGNETIC FIELDS BY 21-CM ZEEMAN SPLITTING

Measurement of the small magnetic field believed to exist in interstellar space has so far eluded both optical and radio techniques. However, the introduction of large radio reflectors offers the possibility of determining longitudinal fields in localized interstellar regions by observing the Zeeman splitting of the 21-cm line of neutral hydrogen.

In the presence of a weak magnetic field, the 21-cm line is split into three components, of frequency (Nafe and Nelson 1948)

$$\nu_0 \qquad (\pi),$$ **1420.4058 MHz**

$$\nu_0 \pm \frac{eH}{4\pi m c} \qquad (\sigma),$$ **1.4 Hz/μG**

where ν_0 is the undisplaced frequency of the line and H the longitudinal component of the magnetic field. Numerically, the frequency difference, $\Delta\nu$, between the two σ components is 2.8 Mc/s per gauss. Thus a magnetic field of 10^{-5} gauss, such as is believed to exist in the Galaxy, gives $\Delta\nu \approx 30$ c/s.

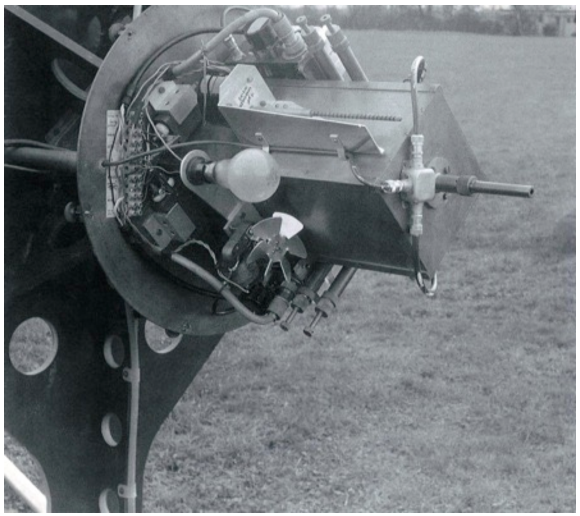
Under normal circumstances the detection of such small shifts in the galactic emission profiles would hardly be possible, owing to their large Doppler broadening. On the other hand, relatively narrow profiles have been observed in absorption. Hagen, Lilley, and McClain (1955) have reported three narrow absorption lines in the 21-cm spectrum of the discrete source in Cassiopeia, presumably due to three individual H I concentrations with different radial velocities. These lines have half-widths of about 10 kc/s, in the center of which the radiation is almost completely absorbed. It may reasonably be assumed that the magnetic field is sensibly constant in direction over any one of the H I concentrations responsible for the absorption lines.

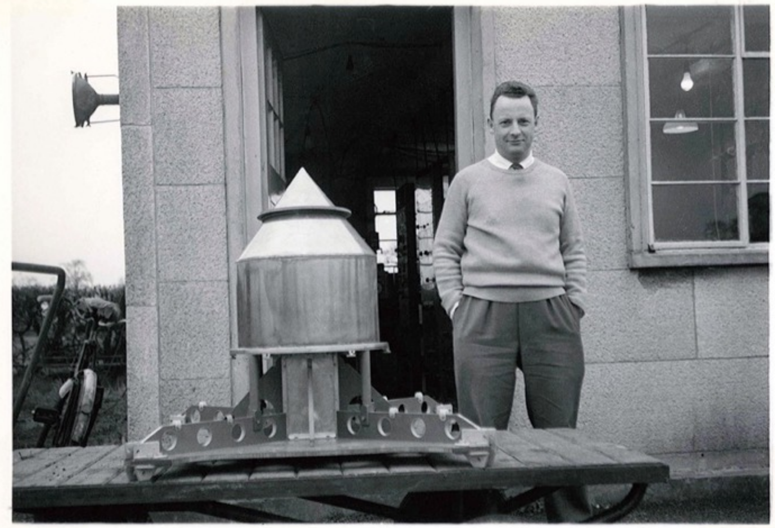
The detection of a Zeeman shift less than 1 per cent of the line width could be accomplished by using the radio analogue of the optical method currently employed by Babcock (1953) for measuring weak solar fields. The frequency of a narrow-band receiver is set on the edge of the line near the point of maximum steepness, and the polarization of the antenna is switched to receive the two circular components alternately. The output at the switching frequency is given, in units of antenna temperature, by

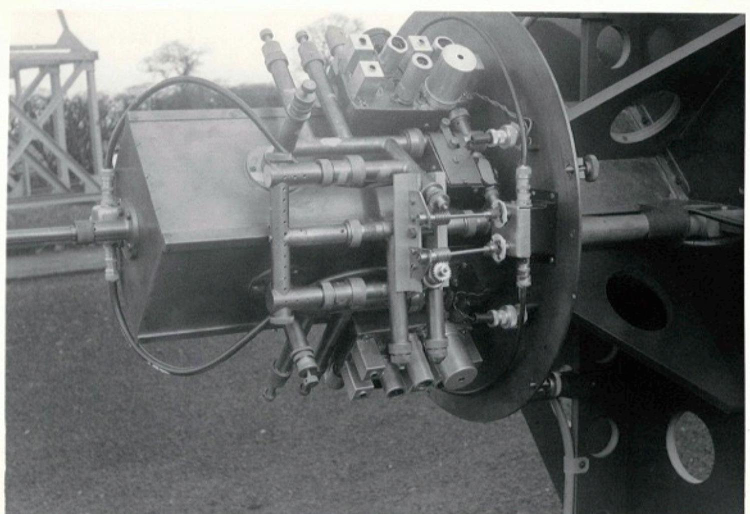
$$\Delta T = \frac{T_a \Delta\nu}{\mu},$$

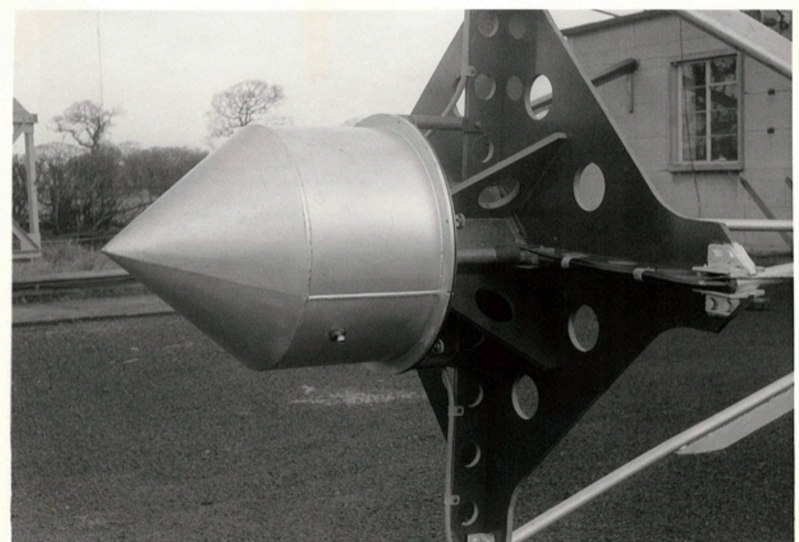
where T_a is the maximum decrease in antenna temperature of the absorption line, $\Delta\nu = 2.8 \times 10^6 H$ c/s is the difference in frequencies between the two σ components, and μ is the half-width of the absorption line, assumed of gaussian profile. Current results indicate values of T_a of the order of 1000° K if the Cassiopeia absorption lines are observed with a 150-foot reflector. Hence, with $\mu = 10$ kc/s, we should expect $\Delta T \approx 3 \times 10^5 H$ degrees. Current techniques permit the detection of $\Delta T \approx 1°$ K ($H \approx 3 \times 10^{-6}$ gauss), and instrumental improvements on this figure are likely in the future.

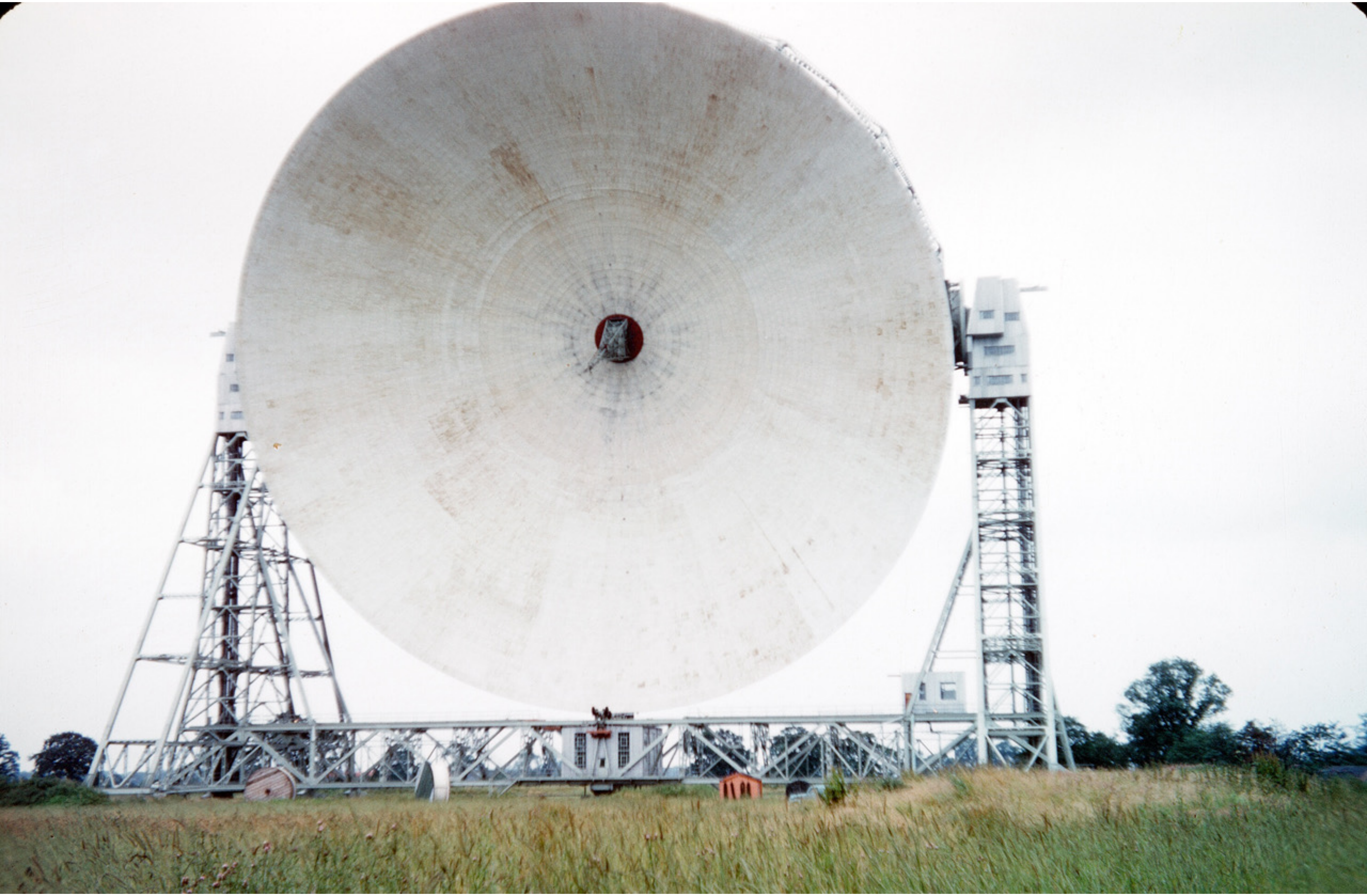
The First 21-cm Zeeman Receiver Built by John Galt



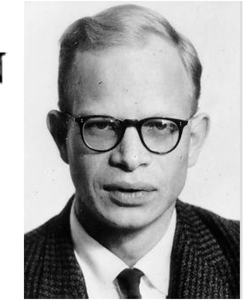








AN ATTEMPT TO DETECT THE GALACTIC MAGNETIC FIELD USING ZEEMAN SPLITTING OF THE HYDROGEN LINE



Bill Shuter (1936-1995)

J. A. Galt, C. H. Slater and W. L. H. Shuter*

(Received 1959 July 1)

Summary

An attempt has been made to determine the strength of the galactic magnetic field by observing the inverse Zeeman effect on the 21 cm absorption line of neutral hydrogen. Preliminary measurements using the Cassiopeia A radio source have shown no detectable Zeeman effect. This indicates that the magnetic field component in the line of sight is less than 5×10^{-5} oersted at the point in the Orion spiral arm where the absorption occurs.

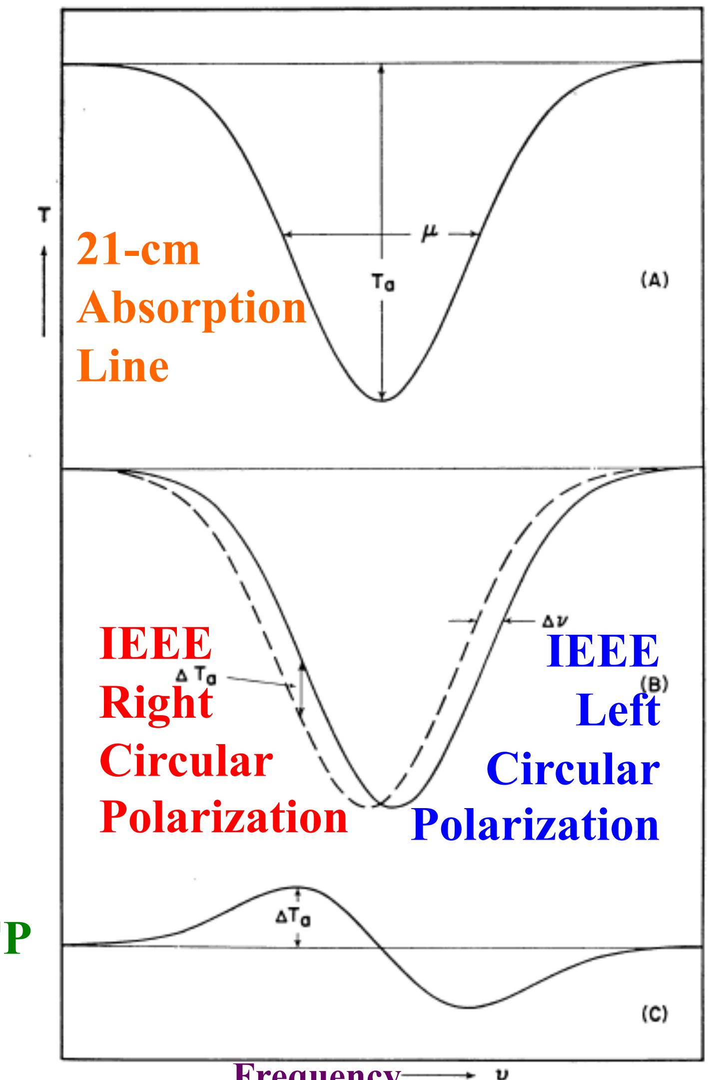
---

1. *Introduction.*—A general magnetic field can be postulated to explain interstellar polarization of starlight, the cosmic ray spectrum, and the stability of the spiral arm structure of the galaxy. According to Chandrasekhar and Fermi (**1**), a magnetic field of the order of 7×10^{-6} oersted may be expected although Davis and Greenstein (**2**) suggest fields up to 10^{-4} oersted.

Bolton and Wild (**3**) have suggested that the galactic magnetic field may be measured by observing the inverse Zeeman effect in the hyperfine structure of the 21 cm absorption spectrum of strong radio sources, using the radio analogue of Babcock's (**4**) method of measuring weak solar magnetic fields. The present paper reports an attempt to make this measurement.

* Now at the Dominion Radio Astrophysical Observatory, Penticton, British Columbia, Canada.

Maximum sensitivity will be obtained with narrow intense lines such as those observed in the absorption spectrum of Cassiopeia A (23N5A) by Hagen, Lilley and McClain (**5**) and by Muller (**6**). The absorption lines originate in individual neutral hydrogen clouds of the galaxy. The narrowest of these lines, which has a half width of about 18 kc/s and is associated with the Orion spiral arm, was studied in this experiment.



Stokes V = RCP - LCP

FIG. 1.—(*A*) *Theoretical profile of absorption line.*
(*B*) *Displaced polarized components of a Zeeman triplet (splitting exaggerated).*
(*C*) *Zeeman effect pattern obtained by subtracting the components in* (*B*).

This is the fingerprint of the Zeeman effect. If we see this, we can extract the magnetic field strength and direction in the hydrogen cloud!!!

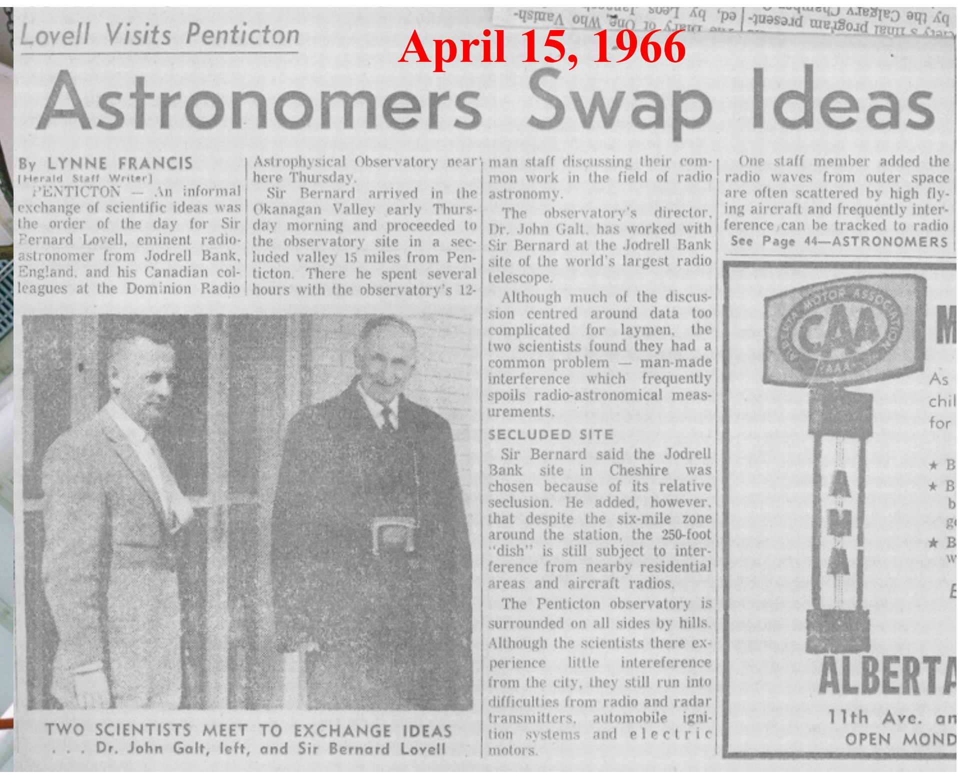
5. *Sensitivity of the equipment.*—The r.m.s. noise on a single polarization record was about 10°K. Substituting the parameters $\Delta T_a = 10°K$, $T_a = 300°K$ and $\mu = 18$ kc/s into equation (2) gives the minimum Zeeman splitting which would be detectable in a single scan as ± 420 c/s. By integrating 16 records this limit is reduced to ± 105 c/s corresponding to a magnetic field of $3{\cdot}8 \times 10^{-5}$ oersted.

In practice this limit was not attained because of a spurious deflection of about 30°K which appeared on all polarization records of Cassiopeia A; its shape corresponding to that of the absorption line. The origin of this spurious deflection was not definitely established, but it is thought to have been caused either by cross-coupling between the probes in the wave-guide or by a systematic difference in gain of the paraboloid to left- and right-handed circular polarization.

Magnetic Field Limit = 38 microgauss

8. *Conclusions.*—No significant Zeeman effect has been detected and it is probable that the longitudinal component of the magnetic field in the clouds of neutral hydrogen which produce absorption is less than 5×10^{-5} oersted. It should be noted that the line of sight in the direction of Cassiopeia A is inclined at an angle of about 45° to the Orion spiral arm so that, if the general magnetic field is aligned with the arm, then the corresponding upper limit to the field must be raised by a factor of $\sqrt{2}$ over that quoted.

9. *Acknowledgments.*—The authors wish to thank Professor A. C. B. Lovell



April 15, 1966

Lovell Visits Penticton

Astronomers Swap Ideas

By LYNNE FRANCIS
[Herald Staff Writer]

PENTICTON — An informal exchange of scientific ideas was the order of the day for Sir Bernard Lovell, eminent radio-astronomer from Jodrell Bank, England, and his Canadian colleagues at the Dominion Radio Astrophysical Observatory near here Thursday.

Sir Bernard arrived in the Okanagan Valley early Thursday morning and proceeded to the observatory site in a secluded valley 15 miles from Penticton. There he spent several hours with the observatory's 12-man staff discussing their common work in the field of radio astronomy.

The observatory's director, Dr. John Galt, has worked with Sir Bernard at the Jodrell Bank site of the world's largest radio telescope.

Although much of the discussion centred around data too complicated for laymen, the two scientists found they had a common problem — man-made interference which frequently spoils radio-astronomical measurements.

SECLUDED SITE

Sir Bernard said the Jodrell Bank site in Cheshire was chosen because of its relative seclusion. He added, however, that despite the six-mile zone around the station, the 250-foot "dish" is still subject to interference from nearby residential areas and aircraft radios.

The Penticton observatory is surrounded on all sides by hills. Although the scientists there experience little intereference from the city, they still run into difficulties from radio and radar transmitters, automobile ignition systems and electric motors.

One staff member added the radio waves from outer space are often scattered by high flying aircraft and frequently interference can be tracked to radio

See Page 44—ASTRONOMERS

TWO SCIENTISTS MEET TO EXCHANGE IDEAS . . . Dr. John Galt, left, and Sir Bernard Lovell

1959 June.

February 1959: 26-m Arrives

Penticton Herald Feb. 19, 1959

RADIO TELESCOPE TRUCKED TO SITE

First truckloads of the 200-ton White Lake radio telescope are being moved from Okanagan Falls to the site three miles away. Here a huge casting and three spars move out, escorted by an RCMP patrol car. The 25 carloads must be moved now, while roads are hard enough to support heavy loads. Assembly will commence in May. (Herald Staff Photo)

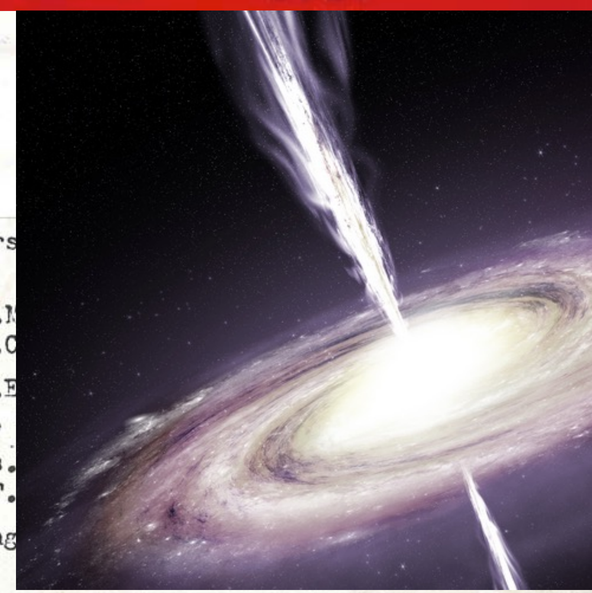
February 1959: 26-m Arrives


DOMINION BRIDGE


OFFICIAL
OPENING
DOMINION
RADIO
ASTROPHYSICAL
OBSERVATORY
MONDAY 20 JUNE 1960
AT 4·00 PM
PENTICTON B.C.

BACK ROW	Dr.T.R.Hartz, Dr.J.L.Yen, M.M.Thomson, Dr.G.Odgers N.Broten, J.Grant, R.W.Tanner, Dr.K.O.Wright.
THIRD ROW	M.Pruesse, A.R.Hamilton, Dr.D.S.Heeschen, Dr.J.H.M Dr.D.C.Rose, R.Grenzeback, Dr.J.W.Warren, Dr.R.M.C
SECOND ROW	Miss M.Burland, Dr.C.H.Costain, Dr.B.W.Currie, P.E Dr.W.Whelau, Dr.B.Oke, Dr.D.E.Hogg, Dr.J.C.Noyes,
FRONT ROW	Dr.P.M.Millman, A.E.Covington, Dr.R.M.Petrie, Mrs. Dr.H.S.Hogg, Dr.C.S.Beals,Dr.G.A.Harrower, Dr.J.F.

ABSENT WHEN PICTURE WAS TAKEN B.L.White, Dr.H.L.Welsh, J.M.Lansing



Tuesday, February 17, 1959 THE PENTICTON HERALD

Radio Telescope 'Ear' To Take Pulse of Space

By BILL STAVDAL
(Herald Staff Reporter)

turn of the earth dims the stars and sends most astronomers home

ment for the Department of Mines and Technical Surveys. Dr. Locke

200 TON INSTRUMENT

Built in Cohasset, Massachusetts, the 200-ton instrument arrived in Penticton Monday aboard 23 freight cars. Another two cars will soon follow through to Okanagan Falls, where unloading is scheduled to begin tomorrow.

From Okanagan Falls the $250,000 listening post will be trucked three miles into White Lake, where construction on several buildings has already begun.

$500,000 Radio Telescope Project Taking Shape at White Lake Site

AUG. 21, 1959

PENTICTON'S RADIOTELESCOPE:

VANCOUVER SUN OCT 16, 1959

$700,000 Worth of Curiosity Sits in a Dish in the Hills

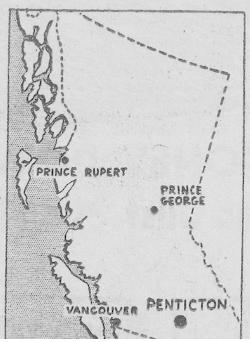
Paul St. Pierre continues his voyage of rediscovery around B.C.

By PAUL ST. PIERRE
Sun Staff Reporter

PENTICTON—The things we call stars, planets and so forth are actually holes in the big wool blanket that covers the earth.

Some day a large hand is going to pull away the blanket and a voice will say: "The show is over now and you must all go home."

However, it must be admitted that there are other theories about the true construction of the universe.



So the Staff Sweats It Out

"Jack," said one of the men in the main building, "Did you realize your office is over the furnace room? You'll get a rumble. And it'll be hot."

"There are only three rooms air-conditioned in the building," Locke explained to me, "Those are rooms with equipment in them. Civil Service regulations. You can air condition equipment rooms but you are not allowed to spend money air conditioning staff rooms."

WHITE LAKE WILL LISTEN

Feb. 27, 1960

When the Heavens Declare Their Glory

By NORMAN GOTRO
Herald Staff Writer

"White Lake is ready."

made great strides in opening up hitherto unknown sources of knowledge is no reason for man to stand still. Were he to do so

Since White Lake Observatory has been established with $750,000 of taxpayers' money and is the outcome of four year's hard work by federal civil servants, one might ask what practical value these far-distant studies have.

BANK OF CANADA
BANQUE DU CANADA

...that cost:	$	750,000.00	in	1960
...would cost:	$	6,411,290.32	in	2018

FOUR THOUSAND YEARS: ONLY ONE-FIFTH OF THE WAY

THE PENTICTON HERALD 2
Thursday, June 23, 1960

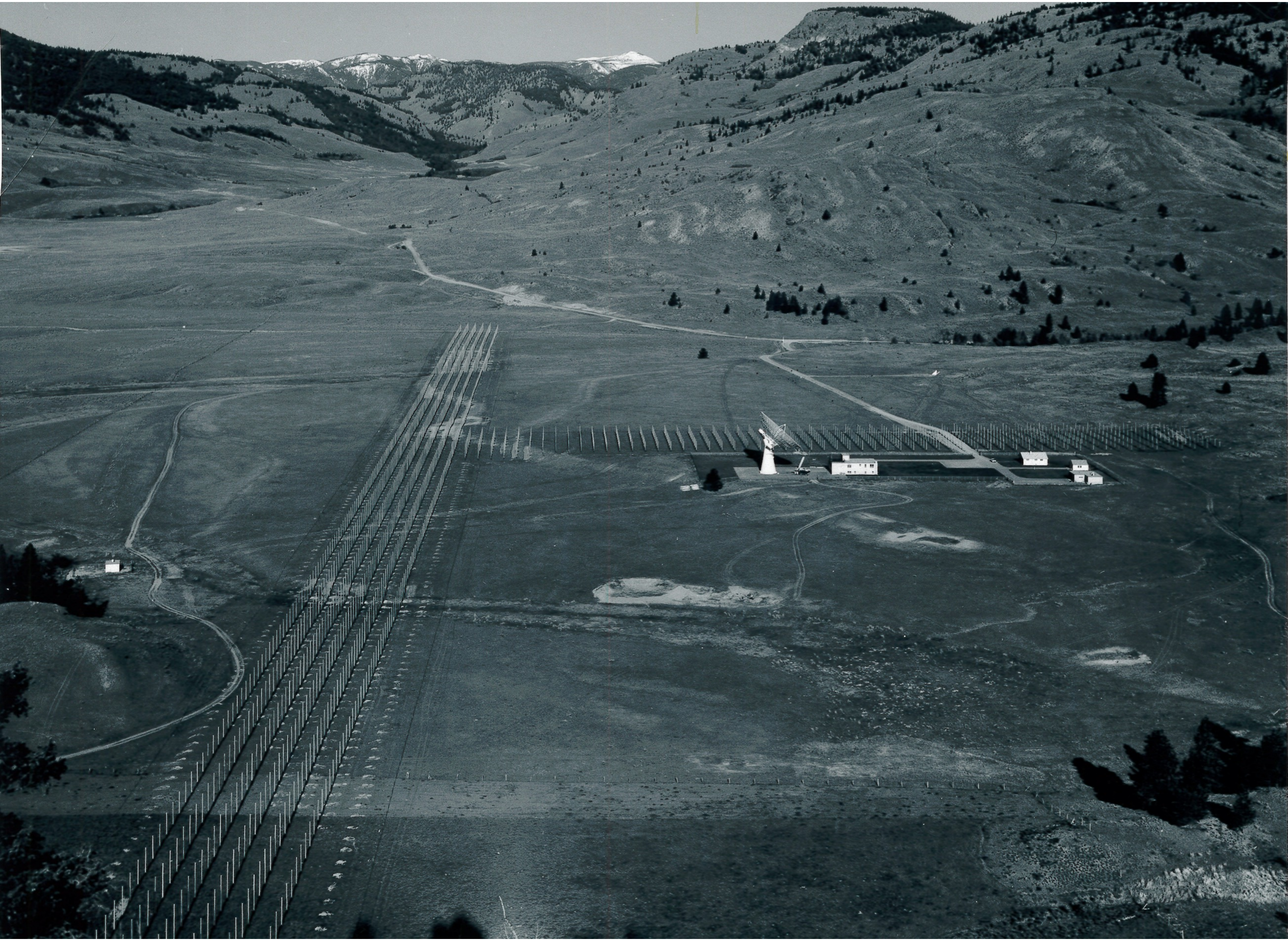
B.C. Expert Evaluates Astronomy

Four thousands years of research have brought explorers general information of only one-fifth of the Milky Way.

But radio-astronomy is expected to spur considerable advance in space research and Canada's "big ear" — the new 84-foot, $750,000 radio-telescope at nearby White Lake — will make a major contribution in man's

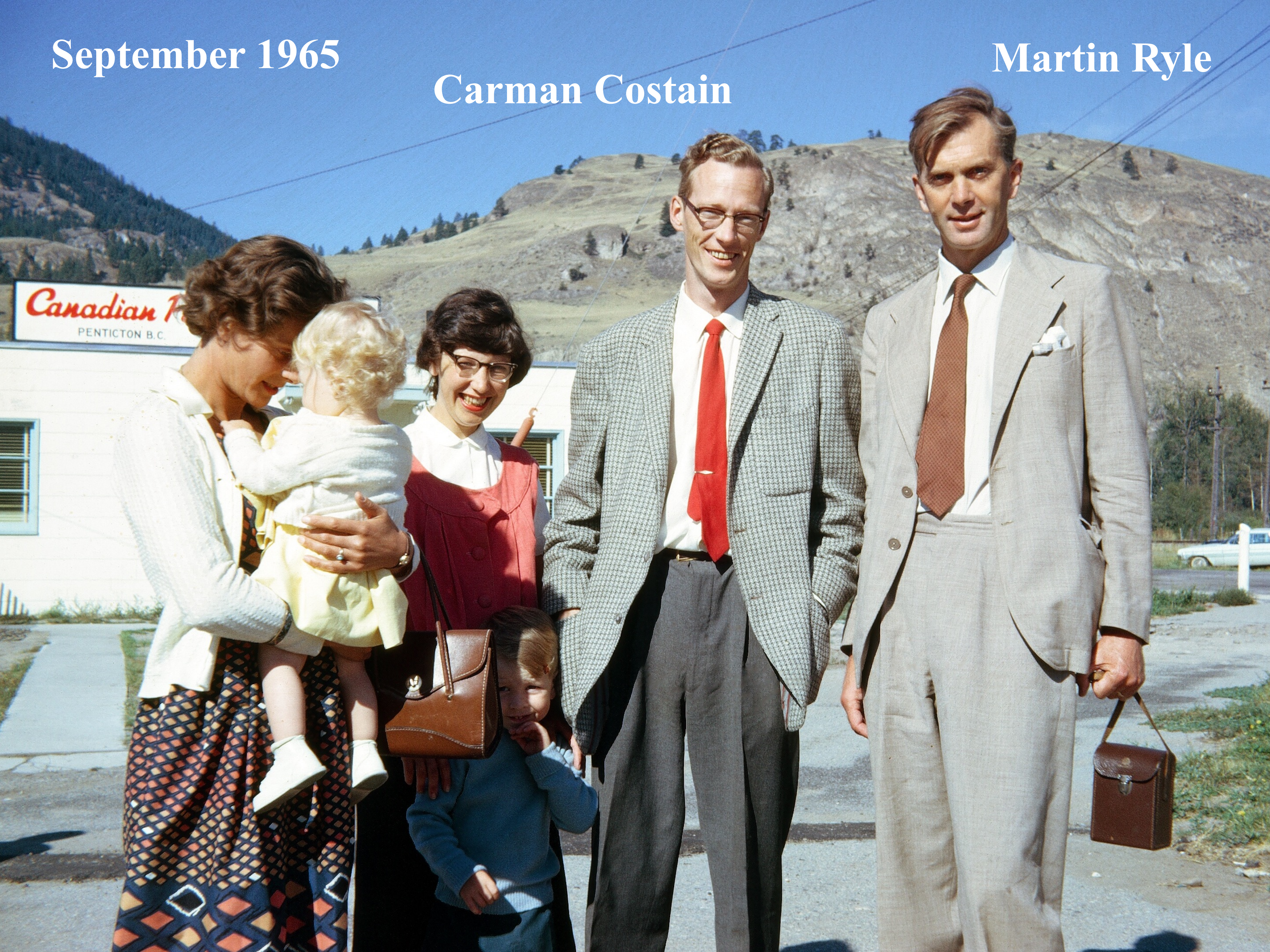
CHIME: $17M CAD

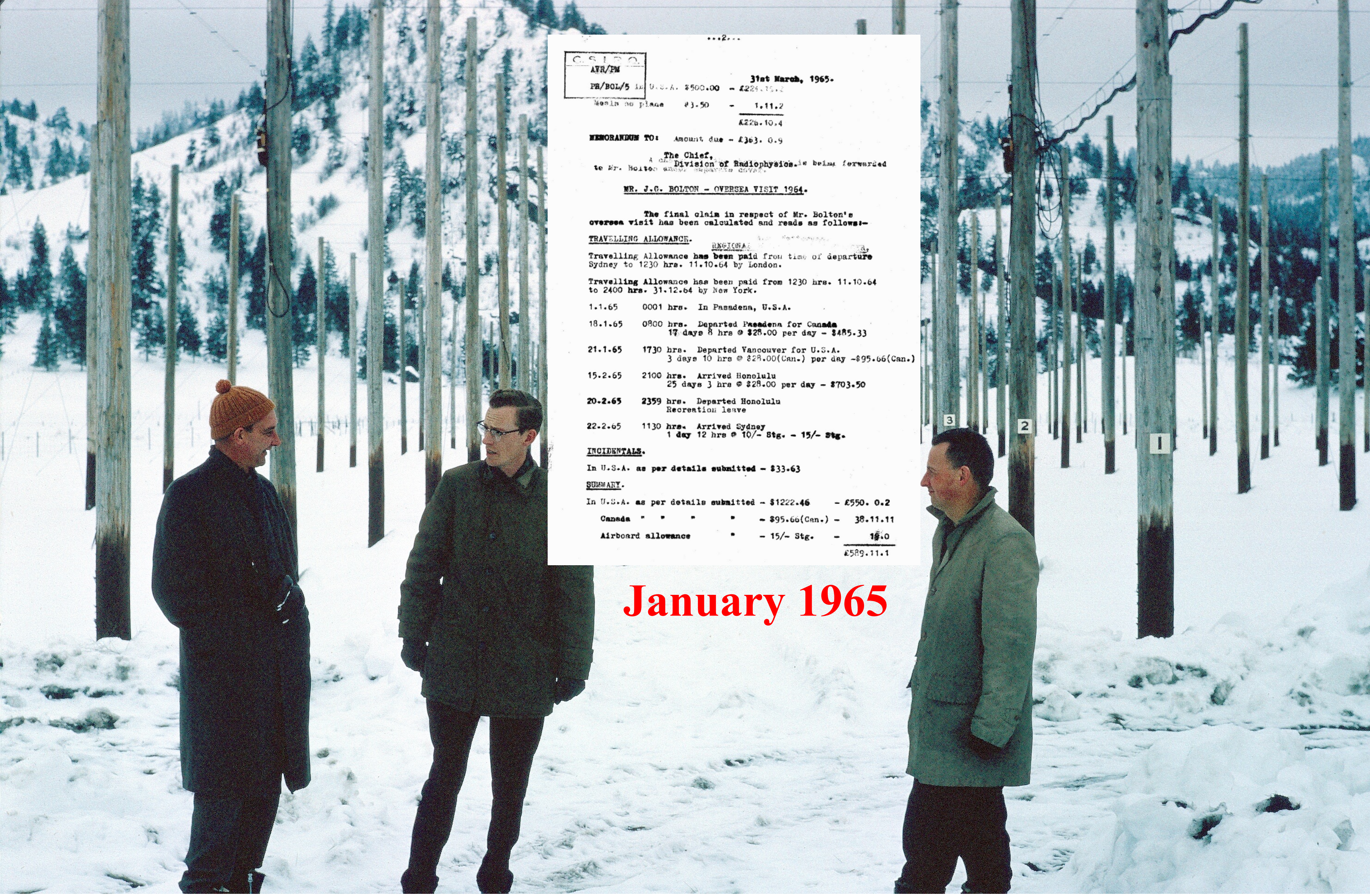
The 22.5 MHz Array



Carman Costain (1932-1989): 1st Canadian to earn Ph.D. in Radio Astronomy

Credit: John Shakeshaft


September 1965
Carman Costain
Martin Ryle
Canadian
PENTICTON B.C.



...2...

C.S.I.R.O.
AVR/PM
PR/BOL/5

31st March, 1965.

In U.S.A. $500.00 – £224.15.2
Meals on plane $3.50 – 1.11.2
£226.10.4
Amount due – £363. 0.9

MEMORANDUM TO: The Chief,
Division of Radiophysics.

... is being forwarded to Mr. Bolton ...

MR. J.G. BOLTON – OVERSEA VISIT 1964.

The final claim in respect of Mr. Bolton's oversea visit has been calculated and reads as follows:-

TRAVELLING ALLOWANCE.

Travelling Allowance has been paid from time of departure Sydney to 1230 hrs. 11.10.64 by London.

Travelling Allowance has been paid from 1230 hrs. 11.10.64 to 2400 hrs. 31.12.64 by New York.

1.1.65 0001 hrs. In Pasadena, U.S.A.

18.1.65 0800 hrs. Departed Pasadena for Canada
17 days 8 hrs @ $28.00 per day – $485.33

21.1.65 1730 hrs. Departed Vancouver for U.S.A.
3 days 10 hrs @ $28.00(Can.) per day –$95.66(Can.)

15.2.65 2100 hrs. Arrived Honolulu
25 days 3 hrs @ $28.00 per day – $703.50

20.2.65 2359 hrs. Departed Honolulu
Recreation leave

22.2.65 1130 hrs. Arrived Sydney
1 day 12 hrs @ 10/- Stg. – 15/- Stg.

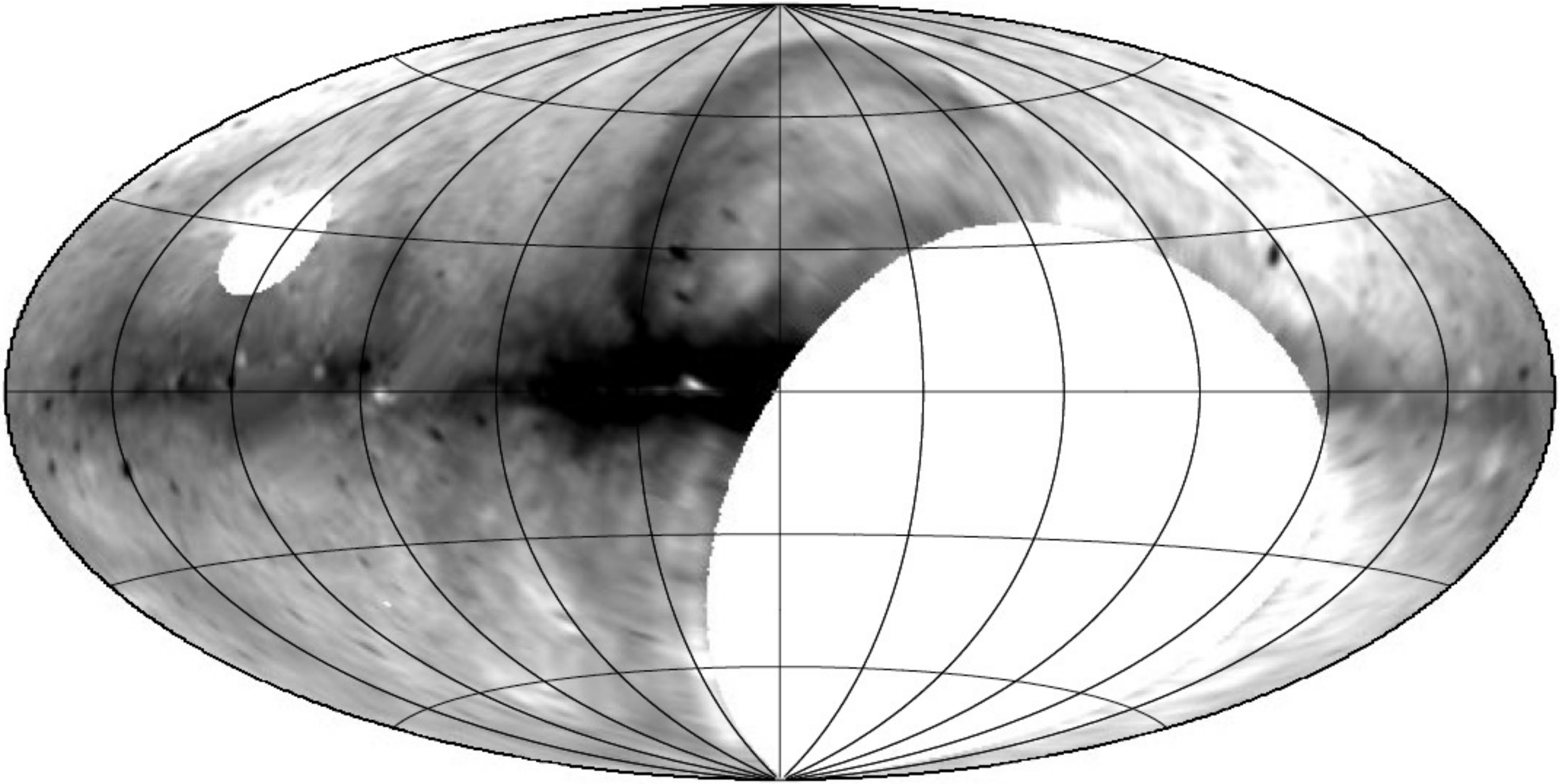
INCIDENTALS.

In U.S.A. as per details submitted – $33.63

SUMMARY.

In U.S.A. as per details submitted	– $1222.46	–	£550. 0.2
Canada " " " "	– $95.66(Can.)	–	38.11.11
Airboard allowance "	– 15/- Stg.	–	15.0
			£589.11.1

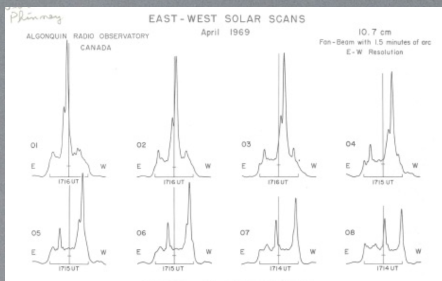
Bolton **Costain** **Galt**



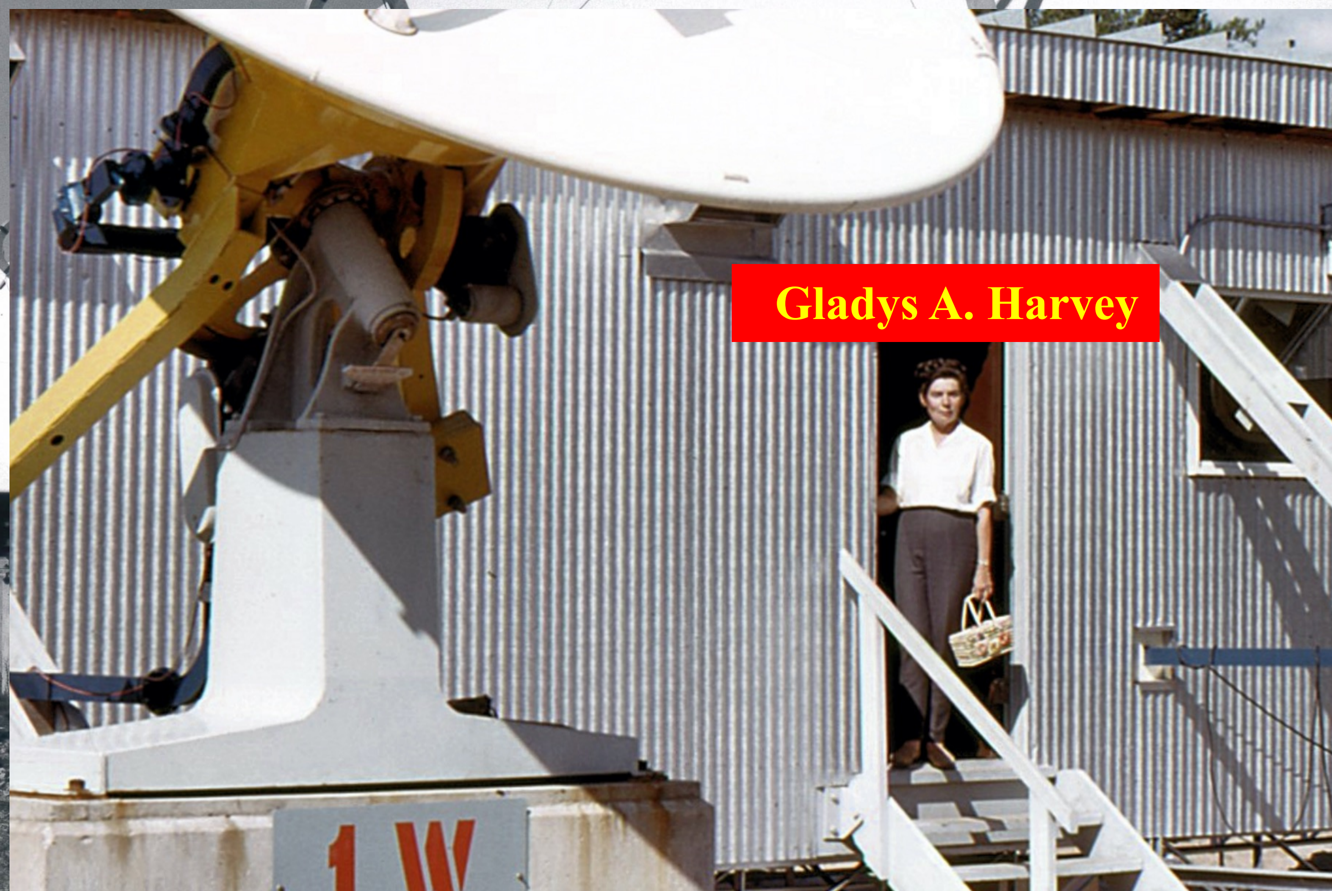
Algonquin Radio Observatory

ARO Solar Interferometer

Forty 3-m dishes along a 1 km E-W baseline



Daily drift curves for part of the month of April



30 Aug 1960

Canada To Build Giant Telescope

PEMBROKE (CP) — A giant new radio telescope that will help astronomers unravel more of the mysteries of outer space is being planned by the National Research Council.

The huge listening post, designed to pick up faint radio waves given off by objects in outer space, will be erected at the NRC radio observatory in Algonquin Park in central Ontario once the project has government approval.

The proposed telescope, costing in excess of $500,000, will be similar in design to one put into operation June 20 by the Dominion observatory near Penticton, B.C. However, it will not duplicate work at the Penticton station.

Biggest In Country

NRC officials at the Algonquin Park observatory, located on the south shore of Lake Traverse, some 120 miles northwest of Ottawa, said the telescope will be the biggest in Canada and among the largest in the world.

A radio telescope has no lens like ordinary optical telescopes. A dish-shaped antenna picks up radio waves from outer space which are fed into complicated recording equipment to be analyzed.

The antenna of the new telescope will be 120 feet in diameter, compared with 84 feet at Penticton.

Many stars, gas clouds and other objects in outer space cannot be detected with optical telescopes. However, their composition can be analyzed thr... study of the radio waves shoot out.

The proposed new teles... will be designed to study ... waves of different freque... than those being examined ... the Penticton operation.

A 33-foot radio telescope ... is under construction at the ... gonquin Park site. It will be ... forerunner of the larger ... scope.

New Site Chosen

NRC decided to establish ... Algonquin Park laboratory a... a year ago after it was ag... that a site at Goth Hill, 14 ... south of Ottawa, no longer ... suitable. Equipment in us...

NRC telescope tender bid— decision soon

National Research Council officials are now completing a recommendation for Treasury Board approval on the award of a tender for construction of a 150-foot radio telescope for the council's radio observatory near Lake Traverse, Algonquin Park.

This "dish" telescope will be the largest in Canada and one of the largest in the world.

The NRC recently secured the services of Freeman and Fox, consultant engineers, London, to advise on the award of the tender for the telescope.

Construction of the NRC $2,000,000 Lake Traverse radio observatory has been approved as originally planned for completion in 1964 despite the government's current austerity program.

13 Oct 1960

Ottawa Citizen Newspapers

The Construction of the 150-ft Telecope in the Media

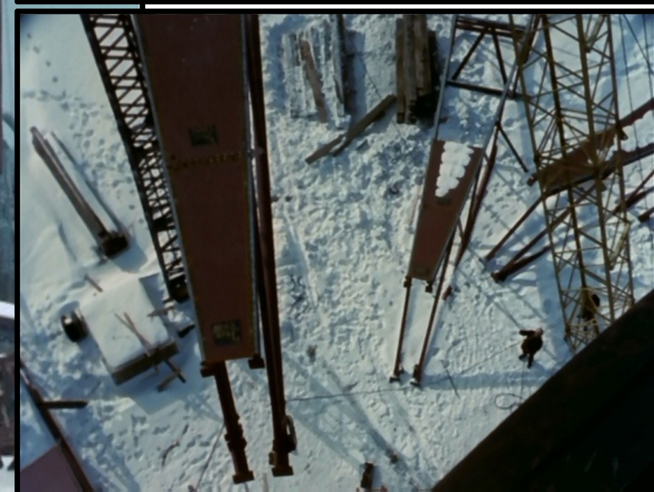
$16M CAD 2018

Canada to Build Giant Telescope, Ottawa Citizen, Aug, 30, 1960, p35
NRC Telescope Tender Bid - Decision Soon, Ottawa Citizen, Oct 13, 1962, p38

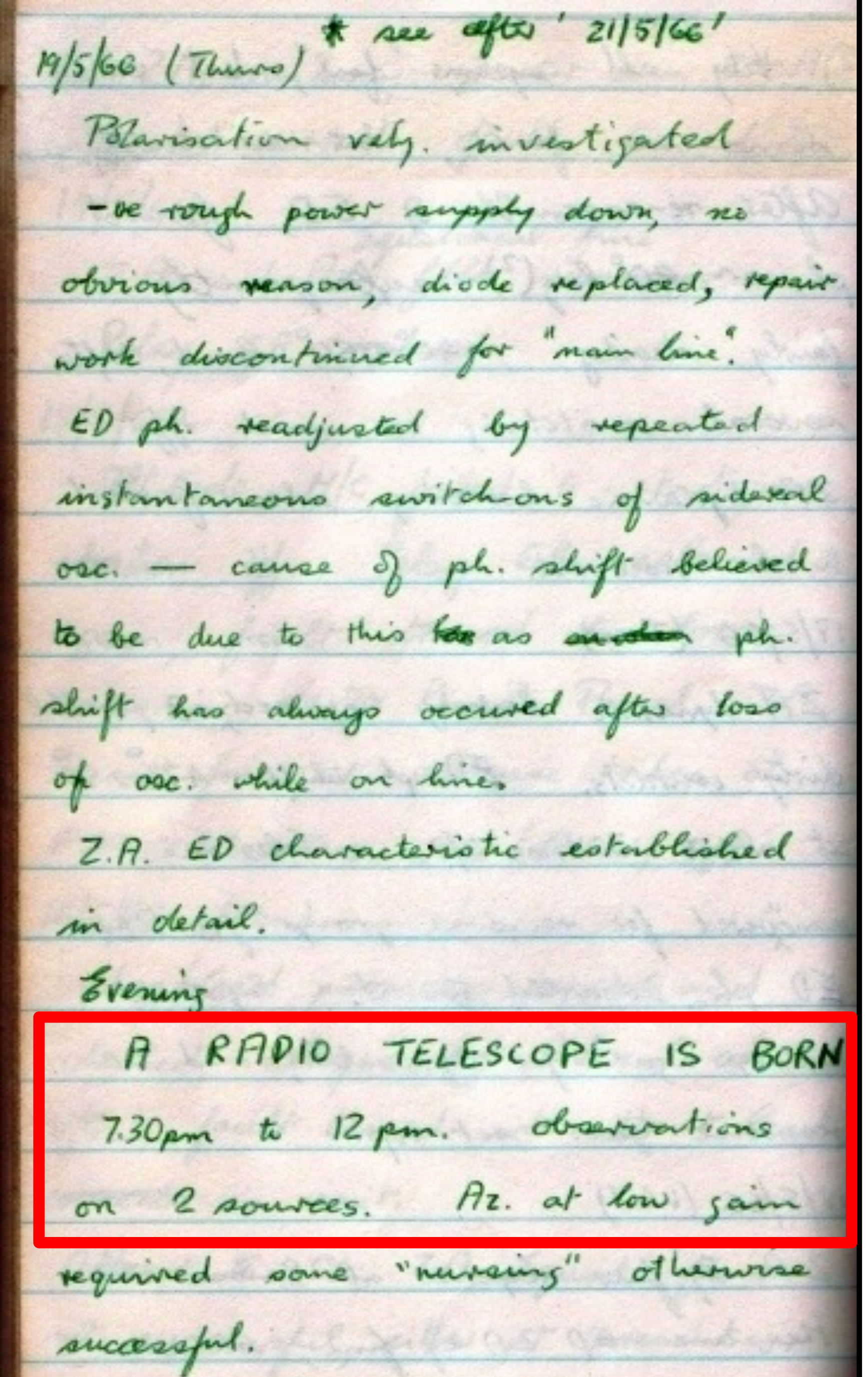
“*To the Edge of the Universe*” (1969)

"To the Edge of the Universe"

Construction of Ribs



19 May 1966
ARO 150-ft "First Light"


19/5/66 (Thurs) * see after '21/5/66'

Polarisation vely. investigated

-ve rough power supply down, no obvious reason, diode replaced, repair work discontinued for "main line".

ED ph. readjusted by repeated instantaneous switch-ons of sidereal osc. — cause of ph. shift believed to be due to this ~~fas~~ as ~~another~~ ph. shift has always occurred after loss of osc. while on line.

Z.A. ED characteristic established in detail.

Evening

A RADIO TELESCOPE IS BORN

7.30pm to 12 pm. observations on 2 sources. Az. at low gain required some "nursing" otherwise successful.

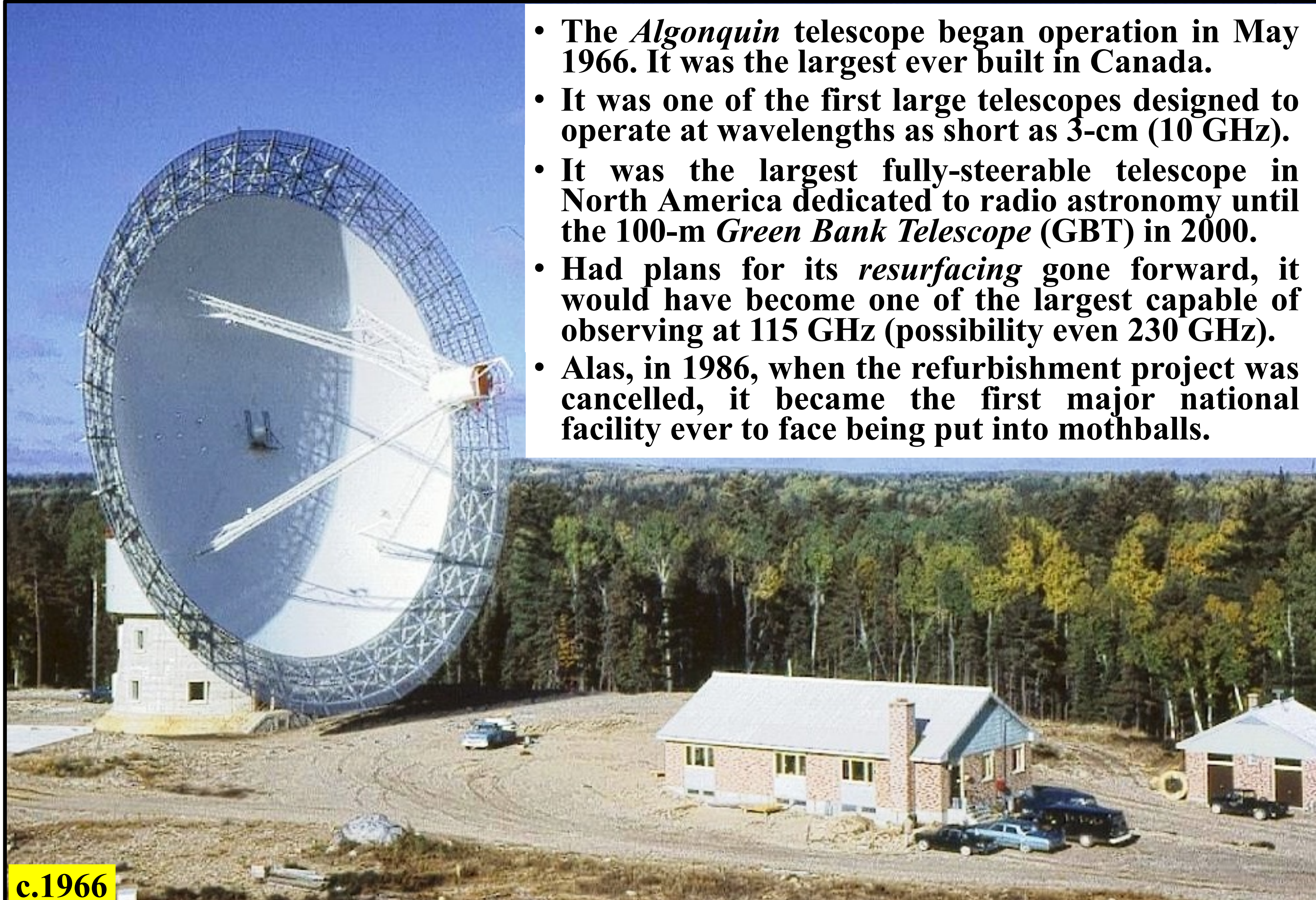
http://www.arocanada.com/ARO/people/John_Kenneth_Ayre.htm

John MacLeod :: "Observational Highlights from the Algonquin Radio Observatory 1959–1986"

Bob Hayward :: "A Brief History of the Algonquin 150-ft Telescope"

Introduction : ARO 150-ft / 46-m Telescope

- **The *Algonquin* telescope began operation in May 1966. It was the largest ever built in Canada.**
- **It was one of the first large telescopes designed to operate at wavelengths as short as 3-cm (10 GHz).**
- **It was the largest fully-steerable telescope in North America dedicated to radio astronomy until the 100-m *Green Bank Telescope* (GBT) in 2000.**
- **Had plans for its *resurfacing* gone forward, it would have become one of the largest capable of observing at 115 GHz (possibility even 230 GHz).**
- **Alas, in 1986, when the refurbishment project was cancelled, it became the first major national facility ever to face being put into mothballs.**

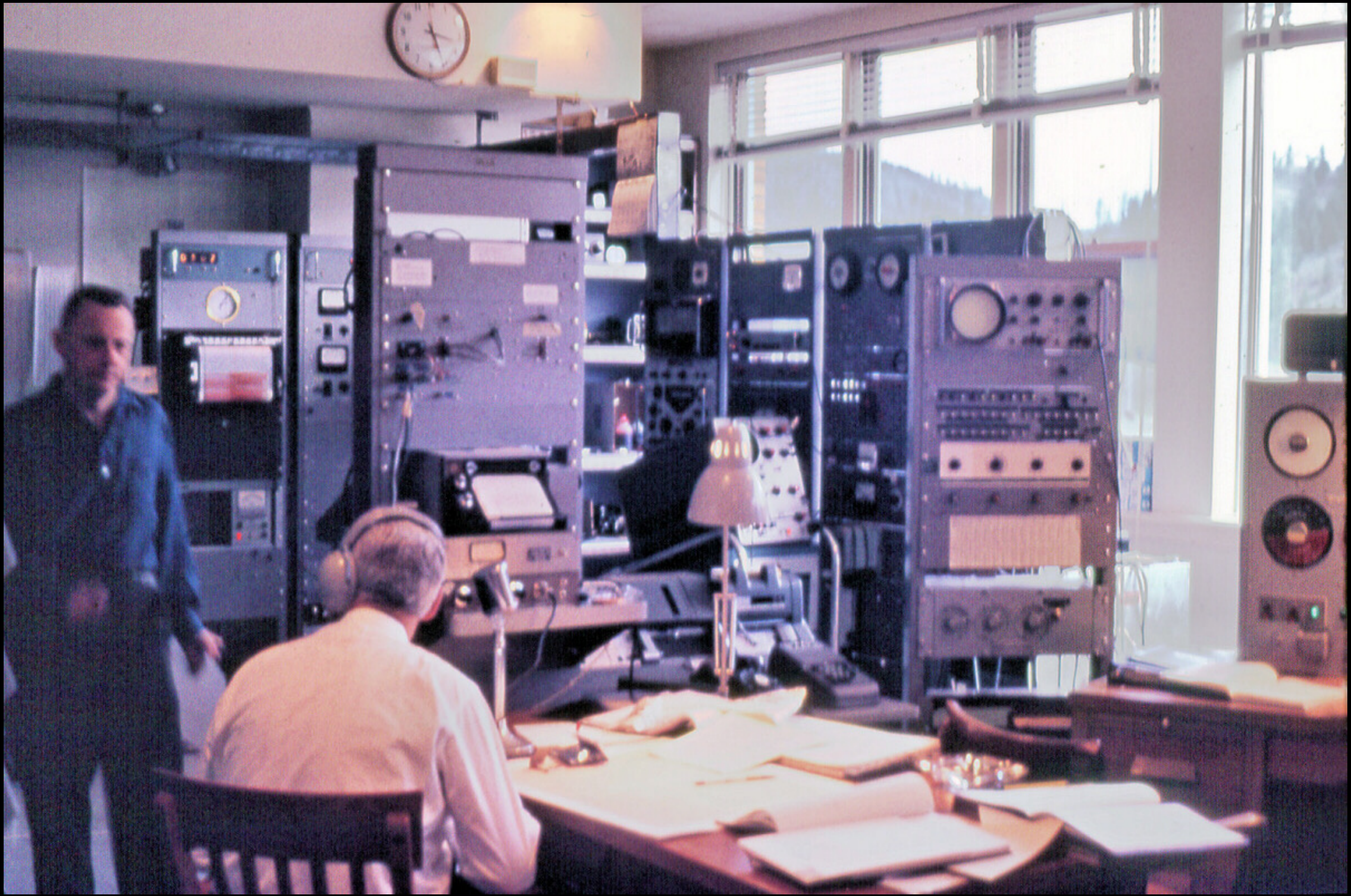


c.1966

http://www.arocanada.com/images/1966_Ken_Site_3_nears_completion.jpg

Joseph Fletcher :: "The Canadian Long Baseline Interferometer"

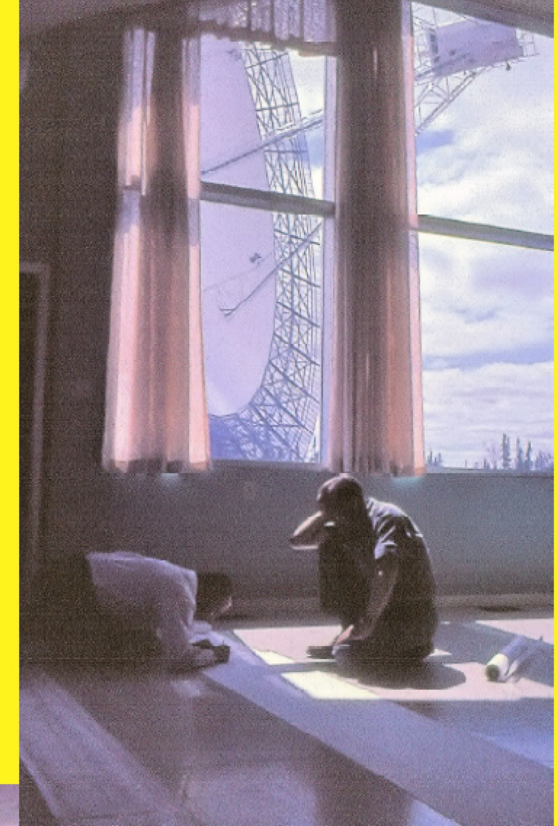
Putting a clock on the train at Chalk River
Joe Fletcher wearing the tie

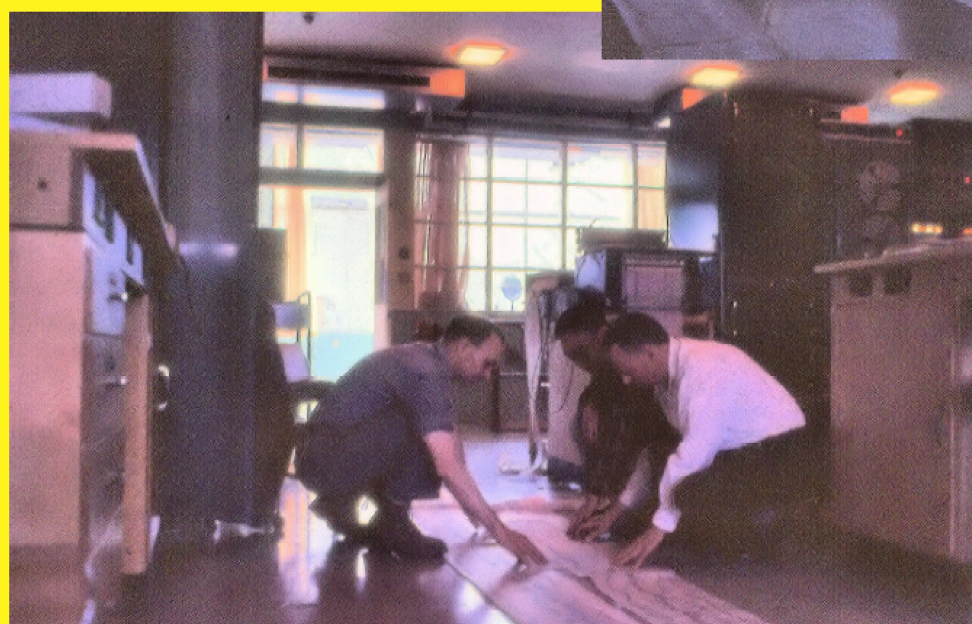


John Galt and Jack Locke in the DRAO control room

“Fringe Searchers” at work …

… Norm
Broten
>>> Allen
Yen
\\\ John
Galt





Leaving Algonquin at 6 a.m. for Ottawa to describe the discovery at the URSI Congress

Long Base Line Interferometry: A New Technique

Abstract. *The technique of using magnetic-tape recorders and atomic frequency standards to operate two widely separated radio telescopes as a phase-coherent interferometer when the stations have no radio-frequency connecting link has been successfully tested at the National Research Council of Canada's Algonquin Radio Observatory.*

In extending conventional radio interferometry to very long base lines two major problems are encountered. The most obvious is the requirement for a phase-stable radio link, but perhaps even more important is the difficulty of compensating for the large and varying difference in arrival time of the signals at the two sites. A flexible technique which overcomes both these difficulties has been developed; it uses video tape recorders and atomic frequency standards.

For radio astronomical applications each tape recorder must have a large signal bandwidth and corresponding time-base stability. If the bandwidth is in excess of 1 Mhz the width of the cross correlation function is less than 1 μsec when the two tapes are correlated on playback. Thus the recorders must be capable of being aligned and of remaining in alignment during playback to within a fraction of a microsecond. To meet these requirements video tape recorders of the type used successfully for many years in television were chosen for the present experiment.

Each station has its own rubidium frequency standard which, during the observing period, is used to derive the frequency of the receiver's local oscillator (since no frequency synchronization between stations is provided) and to provide a time reference. The frequency spectrum of the incoming signal is shifted by the local oscillator to a band centered at zero, so that the receiver output is an undetected, low-pass waveform having a bandwidth of about 1 Mhz. Synchronizing and blanking pulses are then added (so that the composite waveform resembles a television signal without "vertical" pulses) and a recording is made.

Approximately 15 of the 90 minutes of available recording time are allowed to align the machines during playback to within 1 μsec by use of timing pulses

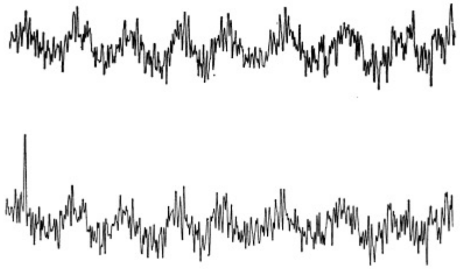


Fig. 1. (Top) An interferometer pattern from the source 3C-294 obtained directly while a recording was being made. (Bottom) An interferometer pattern from the source 3C-294 obtained on playback. The recorded signals were those correlated directly to produce the pattern in the top part of the figure.

recorded from the rubidium standard and a simple counting procedure on the sound track. The synchronizing pulses recorded during the observing period keep the machines locked together to within ±0.2 μsec. These pulses are then removed from the output of the recorders before further processing takes place. The resulting waveform has blank intervals which reduce the effective observing time by less than 30 percent but which create no other problem.

The first test was performed at a center frequency of 448 Mhz. The antenna system consisted of the 46-m radio telescope and a 10-m instrument located 200 m away. The two local oscillators were *not synchronized*, each being controlled by its own atomic frequency standard. There was no noticeable evidence of any short-term phase drift in the local oscillators.

Two methods of operation were employed during the experiment. In the first mode the local oscillator frequencies were the same and the natural fringe rate resulted. The effective integration time of the system was about 1 second. In this mode strong sources such as Taurus "A" (1200 flux units) produced almost noise-free sinusoidal fringes. The weakest source observed was 3C-294 (4.5 flux units), and the fringes obtained are shown in Fig. 1.

In the second mode of operation the fringe rate was increased to about 300 hertz. This was achieved by offsetting the frequency of one local oscillator with a frequency synthesizer. After the tape recorder outputs were correlated the resulting signal was passed through a narrow filter tuned to the fringe rate and the output of this filter was detected. This mode of operation is particularly useful when searching for a strong source when time at the two stations is not known accurately. We found that with a source such as 3C-273 we could "scan" the tapes for the correct time delay at rates of up to 1 μsec/sec by altering the speed of one machine. A plot of the square of the autocorrelation function of the recorder output, centered at the correct time delay, appeared clearly above the noise.

Since both receivers were at the same site it was possible to correlate the receiver outputs directly while a recording was being made and to compare the fringes thus obtained with the fringes obtained on playback. Figure 1 (top) shows such a record for the source 3C-294 (approximately 4.5 flux units). The signals in this case were passed through the electronics of the tape recorders, bypassing the recording heads but having the "sync." pulses added and subsequently removed. Figure 1 (bottom) shows the results of correlating the same signals after they were recorded on tape and played back at a later time. It is interesting to note that the noise on the two records is strongly correlated, which indicates that most of it is caused by the receiver and not by the tapes.

The use of video tape recorders and atomic frequency standards as a technique for operating two widely separated radio telescopes as a phase-coherent interferometer appears to be quite sound. Synchronizing the two tapes to within a fraction of a microsecond presents no problem. Using tape recorders and unsynchronized local oscillators does not produce a large degradation in the signal-to-noise ratio.

When the system is extended to very long base lines the initial time delay can be taken into account by delaying the recorded timing pulses at one station. Compensation for the variation in the time delay can be accomplished by the simple expendient of varying the speed of one machine. The accuracy required in the alignment of the tapes depends only on the system bandwidth and not on the length of the base line.

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University of Toronto, Toronto, Ontario

J. A. Galt

Dominion Radio Astrophysical Observatory, Penticton, British Columbia

28 March 1967

Irradiation Effects in Glasses: Suppression by Synthesis under High-Pressure Hydrogen

Abstract. *Glasses synthesized under high pressure of hydrogen showed resistance to certain effects of irradiation. Paramagnetic and light-absorption effects associated with irradiated glasses were diminished by a factor as large as 20 in some glasses. Irradiation increases the concentration of hydroxyl ions, as evidenced by increased absorption in the 2.7-micron (3700 cm⁻¹) infrared region for hydrogen-silica glasses.*

We have shown previously that various gases may be forced into glasses and melts at high temperature by use of high-pressure techniques (*1*). In this study glasses containing up to 8 moles percent of H_2 were synthesized by the following process: The glass was heated to 800°C under hydrogen at pressures as high as 3 kb; then, when equilibrium

Diameters of Some Quasars at a Wavelength of 66·9 cm

The measurement of the diameter of radio sources in the range of 10^{-2} sec of arc or less has recently been made possible by a new technique in radio interferometry. Independent stable local oscillators are used to convert the signals at the two stations to frequencies which are recorded on magnetic tapes. In principle, these long baseline interferometers (LBI) can operate at any separation.

Measurements at 49 cm wavelength with a baseline of 220 km ($4·6 \times 10^5\lambda$) have been reported by the NRAO Arecibo group[1], and at the 18 cm hydroxyl line wavelength with a baseline of 845 km ($4·7 \times 10^6\lambda$) by the MIT–NRAO group[2]. Measurement at 66·9 cm wavelength with baselines of 183 km ($2·7 \times 10^5\lambda$) and 3,074 km ($4·6 \times 10^6\lambda$) have also been reported by the Canadian LBI group[3]. A further series of observations has been made at 66·9 cm with the 3,074 km baseline during the period July 26–29, 1967, in which fringes of amplitude greater than 4 flux units have been detected from eight sources.

Table 1 shows the fringe visibilities determined from both the $2·7 \times 10^5\lambda$ baseline (position angle 103°) and the $4·6 \times 10^6\lambda$ baseline (position angle 95°). The details of the interferometer have been described previously[4]. Most of the observations were taken near the instrument meridian. The fringe amplitudes were determined from artificial fringes produced by the introduction of coherent c.w. signals at each receiver. The level of these signals was commensurate with the total power output from sources of known flux value, taking into account the bandpass characteristics of the system. The fringe visibilities were then derived from comparison with adopted zero spacing flux values as shown in Table 1. The three highest visibilities at the $4·6 \times 10^6\lambda$ spacing and the nine highest visibilities at the $2·7 \times 10^5\lambda$ baseline were nearly equal, and close to unity. A slight adjustment was therefore applied in deriving the values in Table 1 so that the average of each of the groups was normalized to unity. The estimated probable errors of the results are included with each entry. The last column lists source diameters computed on the assumption of a Gaussian model. For sources observed at both separations the data from the longer baseline were used. About forty other sources were observed in the July programme. More elaborate data processing will be necessary, however, to determine their visibilities.

At small elongations interplanetary scintillation could cause a significant reduction in fringe amplitudes. At the time of observation, however, the sources closest to the Sun (*CTA* 21, *3C* 273*B*, *3C* 279 and 1127–14) had elongations from 60° to 75°. From published data[5] it is estimated that the effect of scintillation on fringe amplitude is small. The high visibility of 1127–14 supports this conclusion. The sources, *3C* 273*B*, *3C* 279, *3C* 286, *3C* 309·1 and *CTA* 21 are apparently partially resolved. The detection of fringes at the shorter spacing for the extra-galactic source *3C* 274 supports the suggestion of a small diameter component[6].

Table 1

	S_{448}	Fringe visibility $2·7 \times 10^5\lambda$	Fringe visibility $4·6 \times 10^6\lambda$	Diameter (sec. of arc)
CTA 21	10·5	*	0·5 ± 0·1	0·02
1127–14	5·0	*	0·9 ± 0·2	≤0·01
3C 273*B* †	19·0	1·1 ± 0·2	0·5 ± 0·1	0·02
3C 274	520	0·02 ± 0·01		
3C 279	12·3	0·9 ± 0·2	0·3 ± 0·1	0·03
3C 287	11·8	1·2 ± 0·2		≤0·1
3C 286	22·7	0·9 ± 0·2	0·2 ± 0·1	0·03
3C 298	23·0	1·0 ± 0·2		≤0·1
3C 309·1	14·1	0·7 ± 0·2	0·3 ± 0·1	0·03
3C 345	9·0	0·9 ± 0·2	1·0 ± 0·2	≤0·01
NRAO 530	6·5	0·9 ± 0·2		≤0·1
3C 446	11·4	1·0 ± 0·2 ‡		≤0·3
CTA 102	7·3	1·1 ± 0·2 ‡	1·0 ± 0·2	≤0·01
3C 454·3	14·0	0·4 ± 0·1 ‡		0·6

* Source not included in observing programme.
† It is assumed that *3C* 273*A* is completely resolved at both spacings.
‡ These visibilities were derived for observation laid at the following effective base lines and position angles: *3C* 446, $1·0 \times 10^6$ λ and 120°; *CTA* 102, $1·5 \times 10^6$ λ and 139°; *3C* 454·3, $1·7 \times 10^6$ λ and 143°.

The variations of relative local oscillator phase necessary to keep a source on the same interference fringe for sources *3C* 273*B* and *3C* 345, observed at the longer baseline, were analysed in detail. Over a period of 15 min the variations of apparent local oscillator phase difference with time were fitted with a third order polynomial which approximated the expected variations. The r.m.s. errors were 25° and 70°, respectively. This indicates that even with the relatively low stability of rubidium clocks, valuable information can be derived from phase data for such problems as the synchronization of time and frequency standards at different locations, the determination of relative positions on Earth, the precise measurement of source position and the analysis of source structure. With the more stable hydrogen clocks, the long baseline interferometer will make many new investigations[7] possible.

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Received September 11, 1967.

1 Bare, C., Clark, B. G., Kellermann, K. I., Cohen, H., and Jauncey, D. L., *Science*, **157**, 189 (1967).
2 Moran, J. M., Crowther, P. P., Burke, B. F., Barrett, A. H., Rogers, A. E. E., Ball, J. A., Carter, J. C., and Bare, C. C., *Science*, **157**, 676 (1967).
3 Broten, N. W., Legg, T. H., Locke, J. L., McLeish, C. W., Richards, R. S., Chisholm, R. M., Gush, H. P., Yen, J. L., and Galt, J. A., *Nature*, **215**, 38 (1967).
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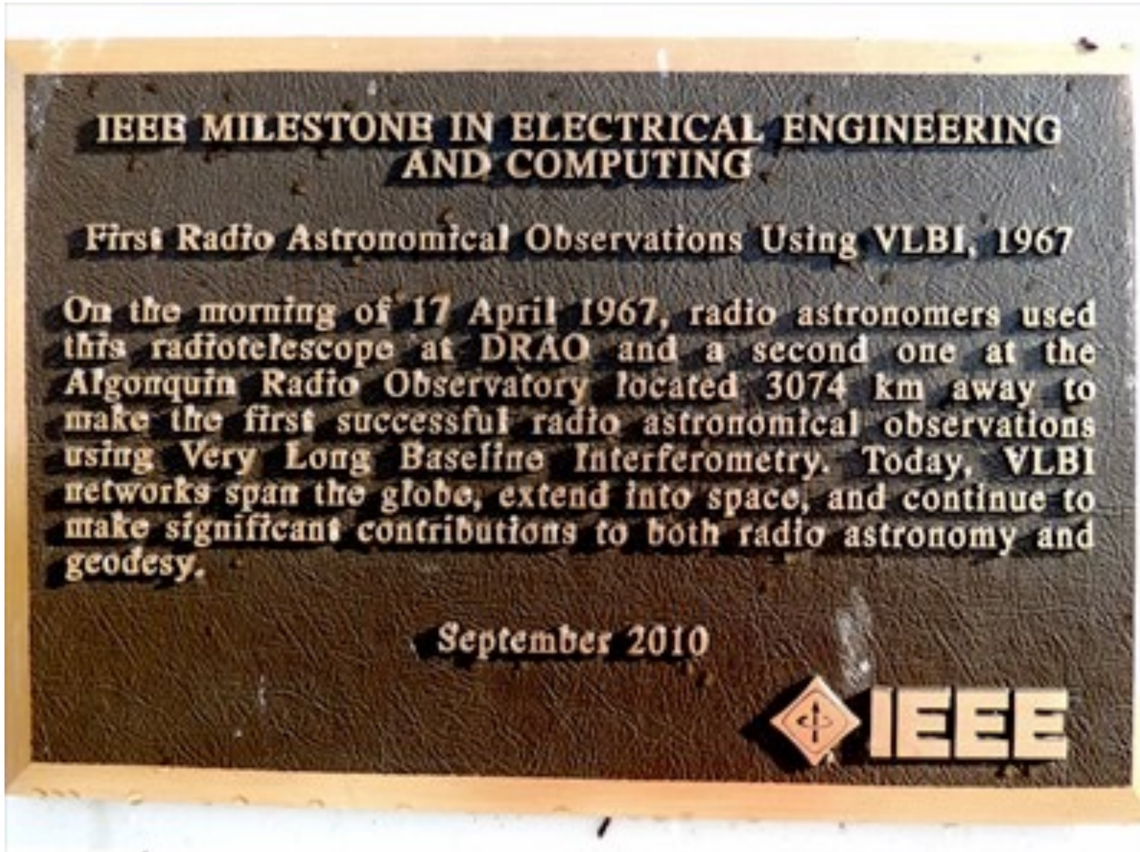
6 Palmer, H. P., Rowson, B., Anderson, B., Donaldson, W., Miley, G. K., Gent, H., Adgie, R. L., Slee, O. B., and Crowther, J. H., *Nature*, **213**, 789 (1967).
7 Gold, T., *Science*, **157**, 302 (1967).

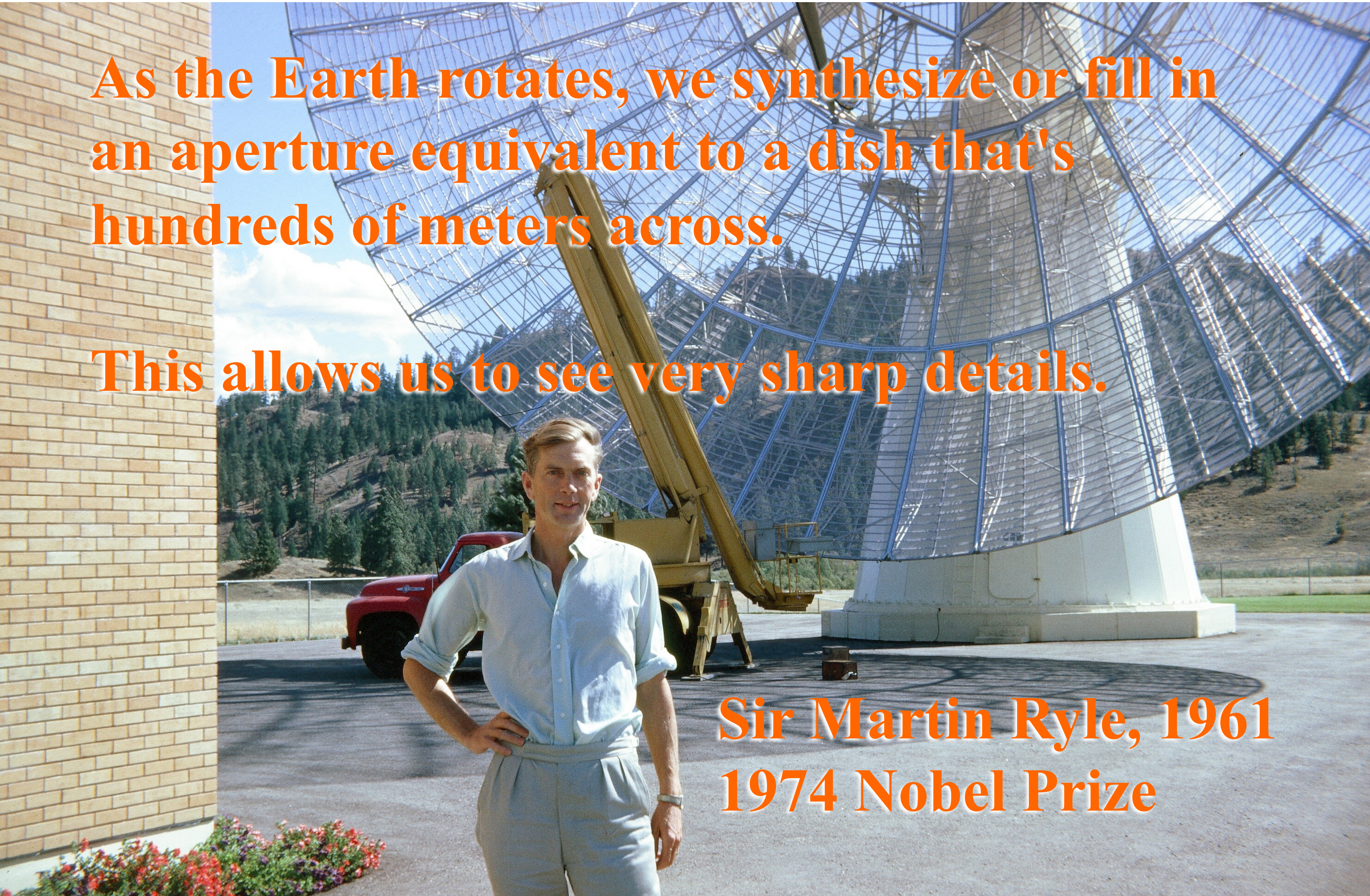
American Academy of Arts and Sciences
1971 Rumford Prize

Institute of Electrical and Electronics Engineers 2010 Milestone Award



- The Pacemaker
- The Integrated Circuit
- Liquid Crystal Display
- The Internet
- The Laser
- The Computer
- The Compact Disc
- The Mercury Spacecraft

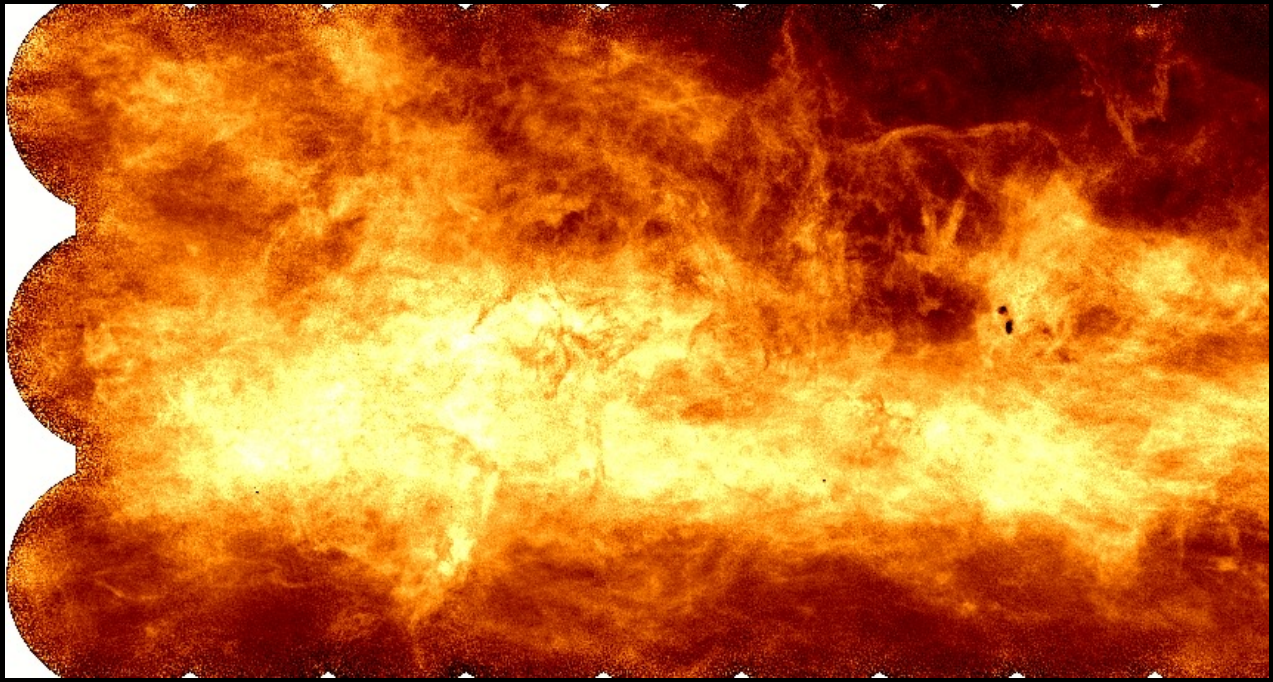
Aperture Synthesis



The DRAO Synthesis Telescope

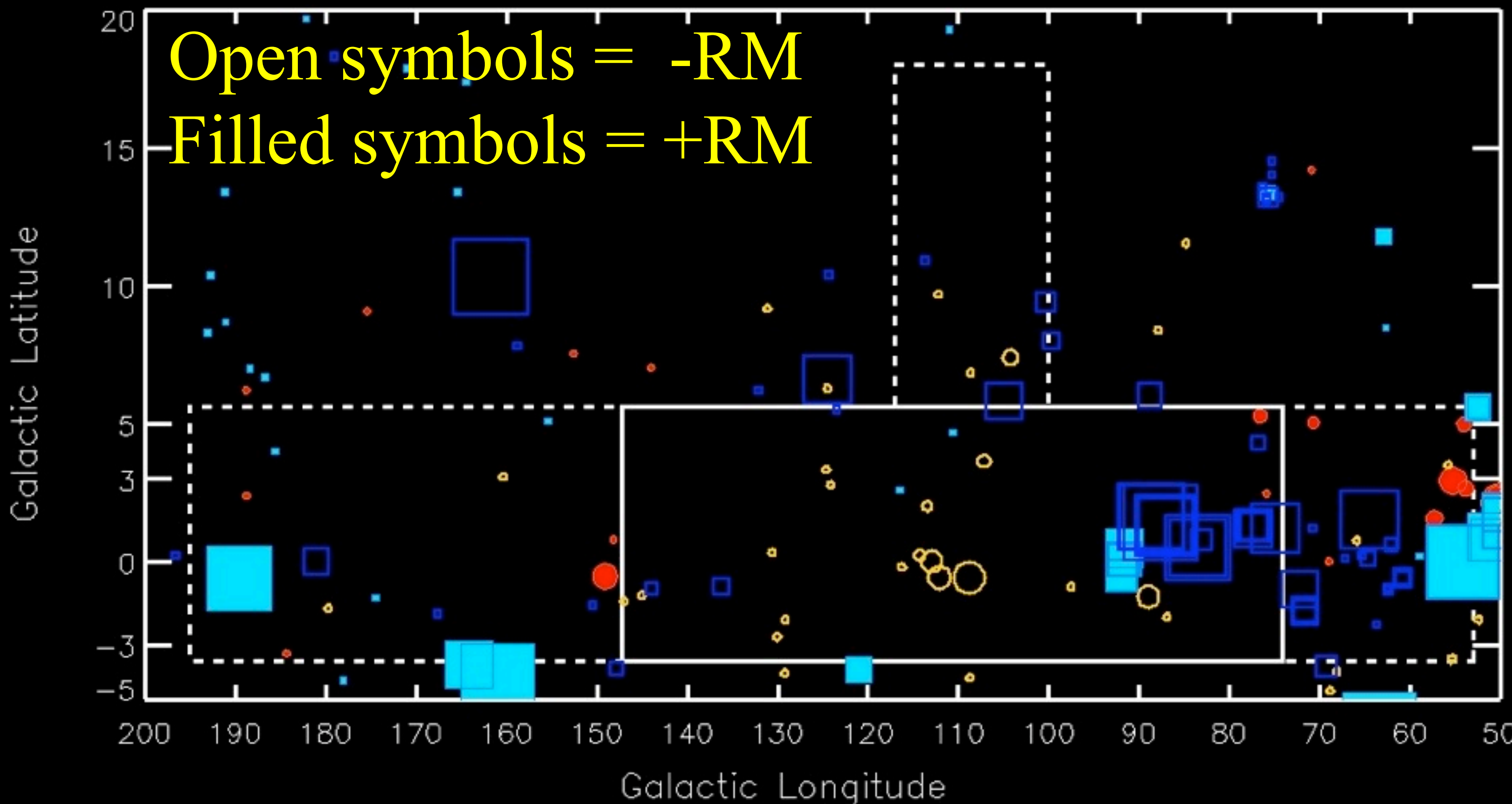
What can this synthesis telescope do for our pictures of space?

This is an image of radio waves from hydrogen gas between the stars.



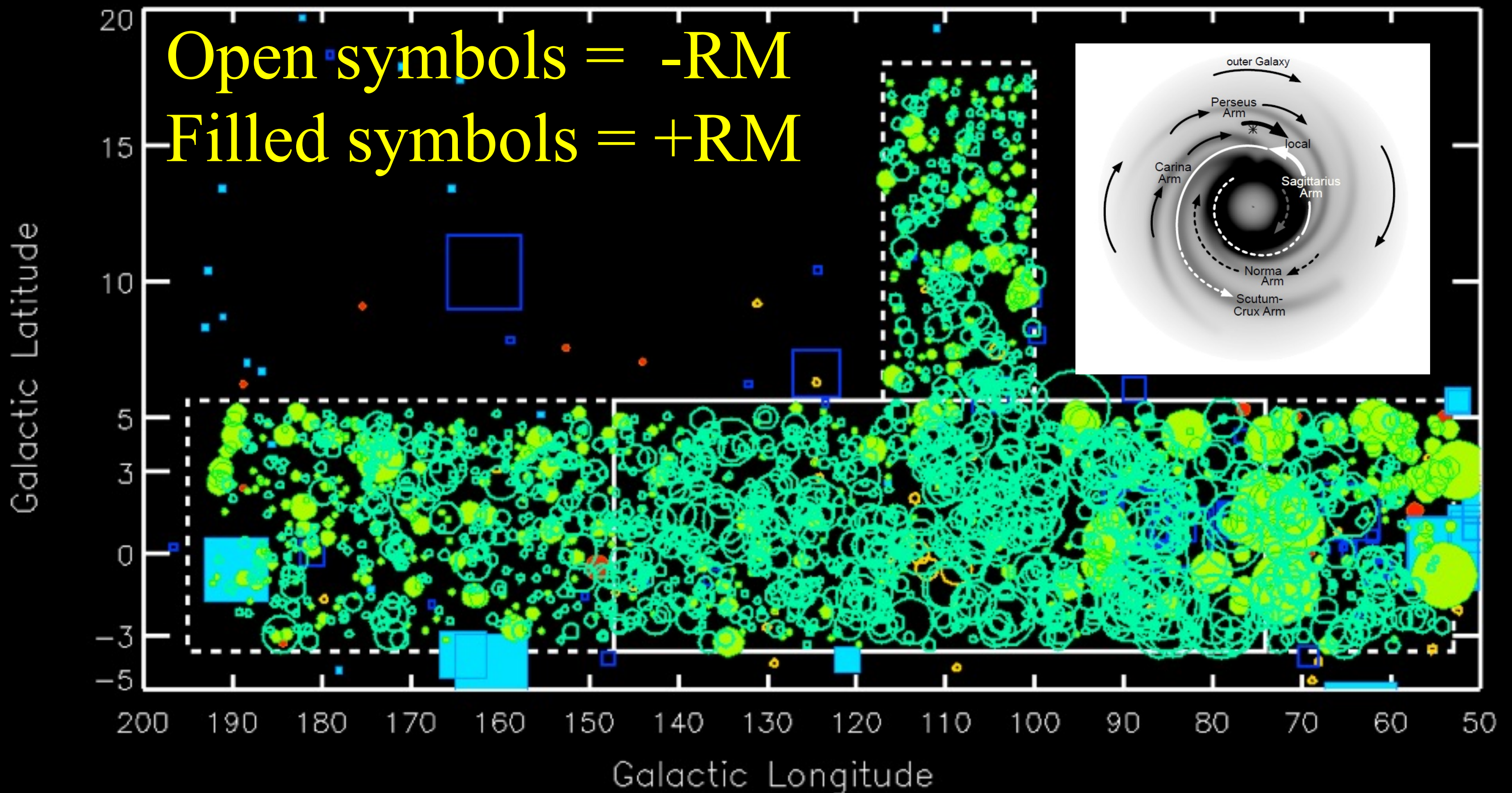

The Canadian
Galactic Plane Survey
180°
90°

Faraday Rotation Measure Sources in the CGPS…



Published as of 2001: 27 pulsars, 40 EGS

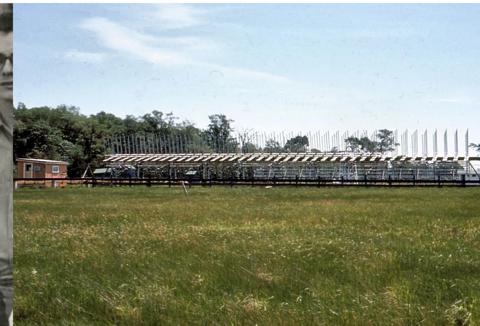
…with the latest data (2015).

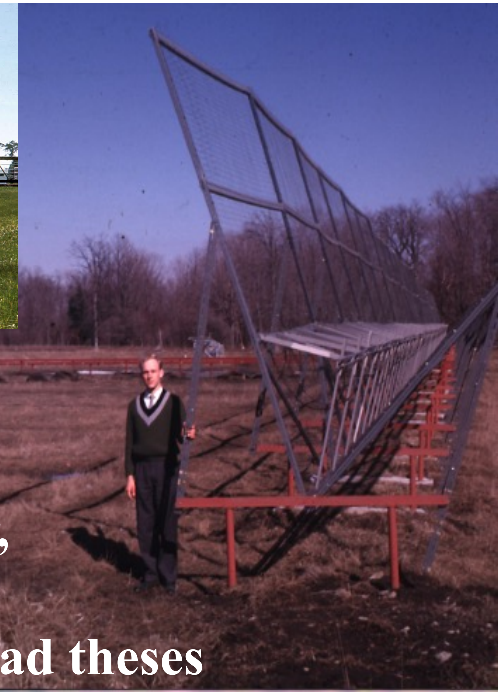


>1500 new RM sources in the CGPS region!

Queen's Radio Observatory: A Canadian Training Ground

Phil Kronberg **Bill McCutcheon**

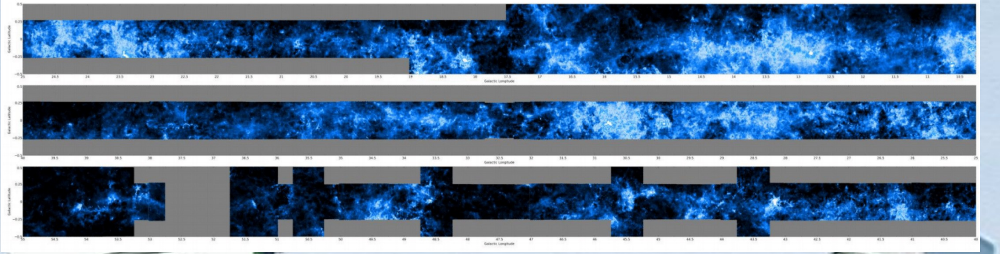


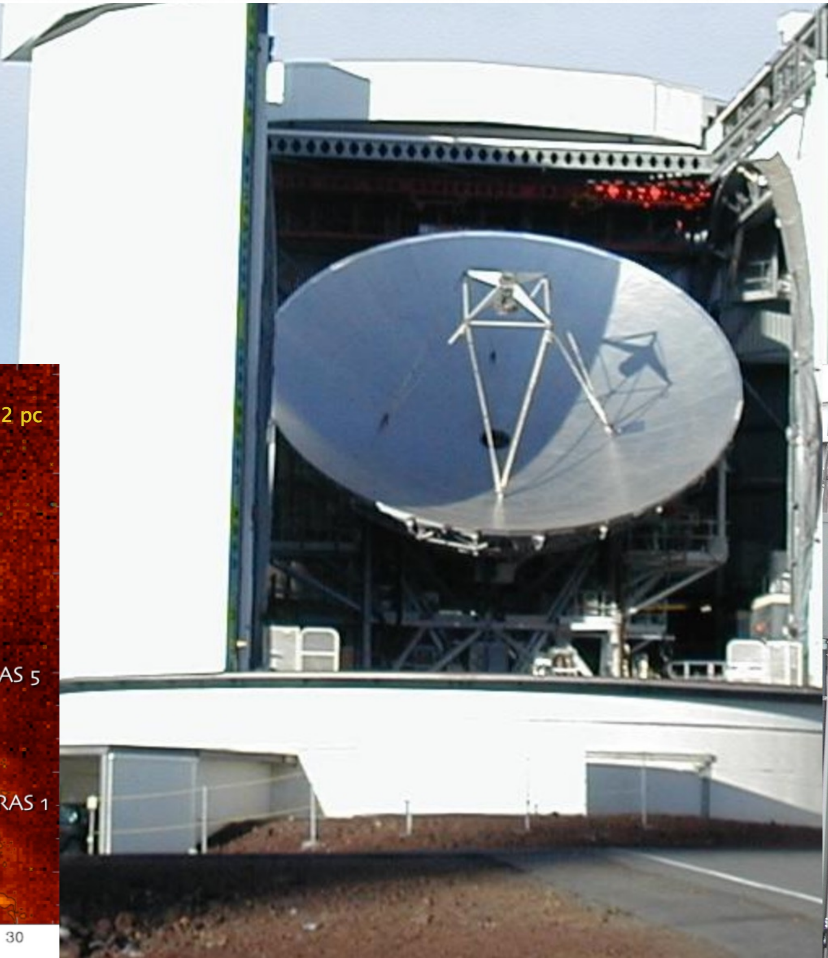


1962-75
Vic Hughes,
George Harrower,
Alan Bridle
supervised 20+ grad theses

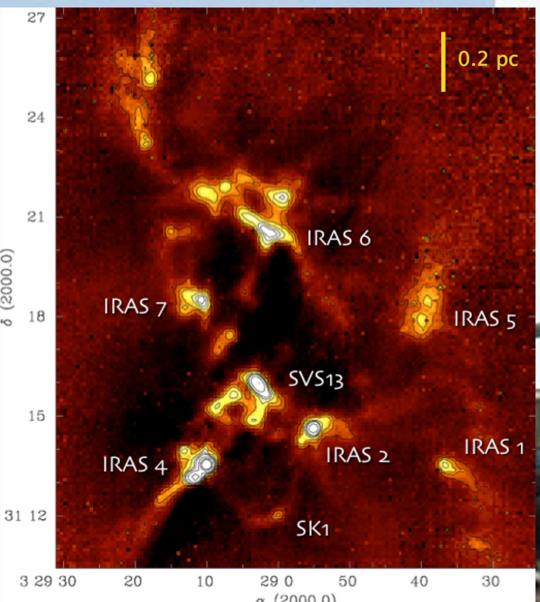
James Clerk Maxwell Telescope (JCMT)

Canada Gets into Star Formation





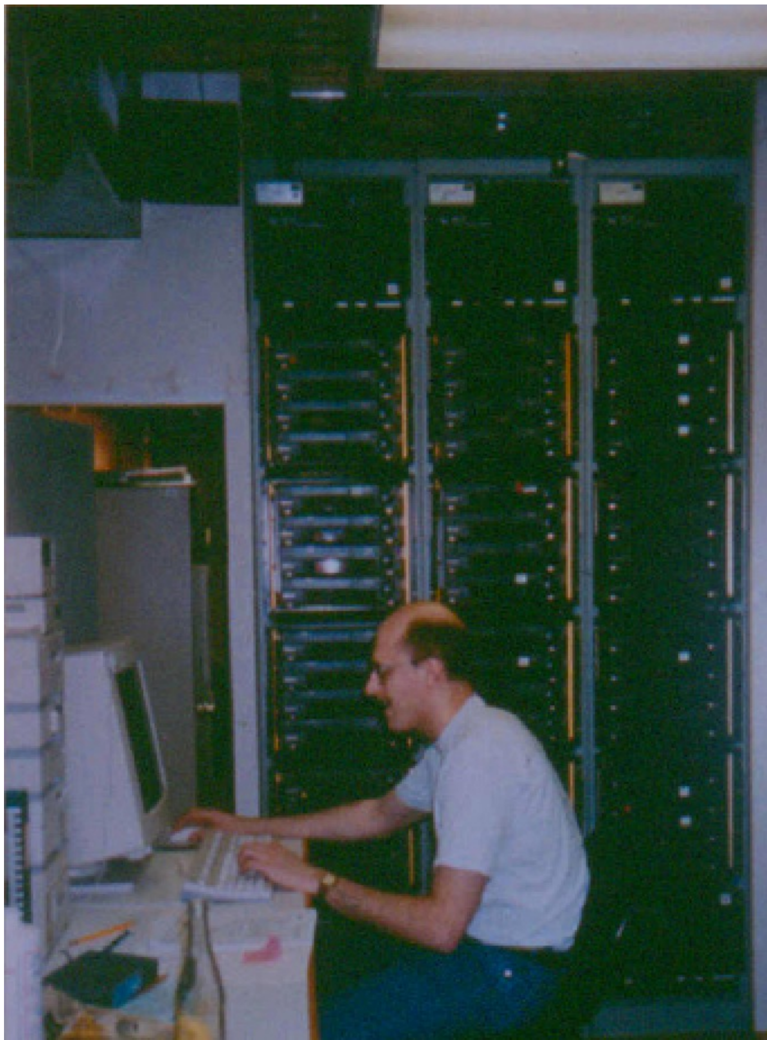
ACSIS: Spectral Line Backend



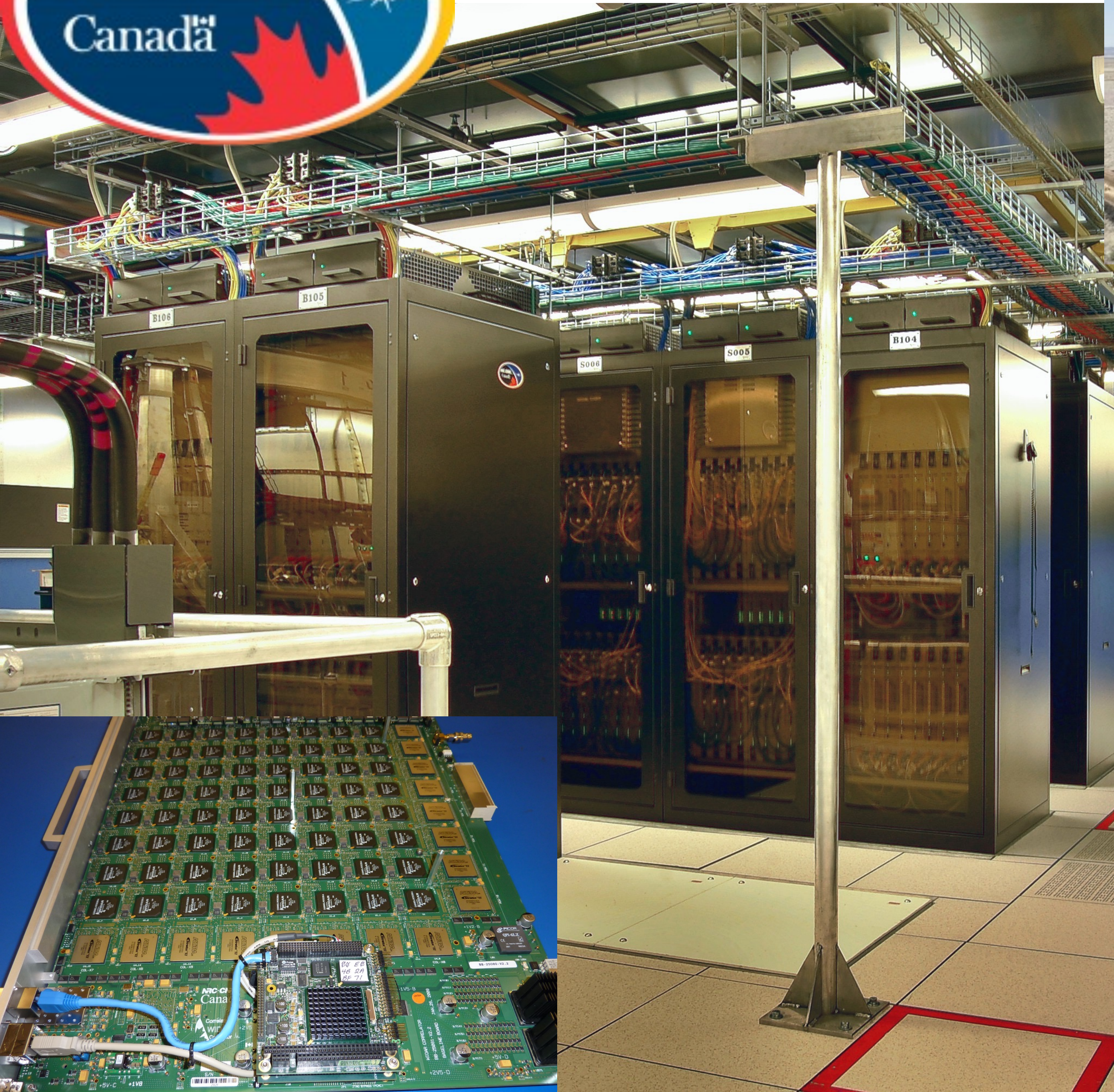
VSOP:

VLBI Space Observatory Program

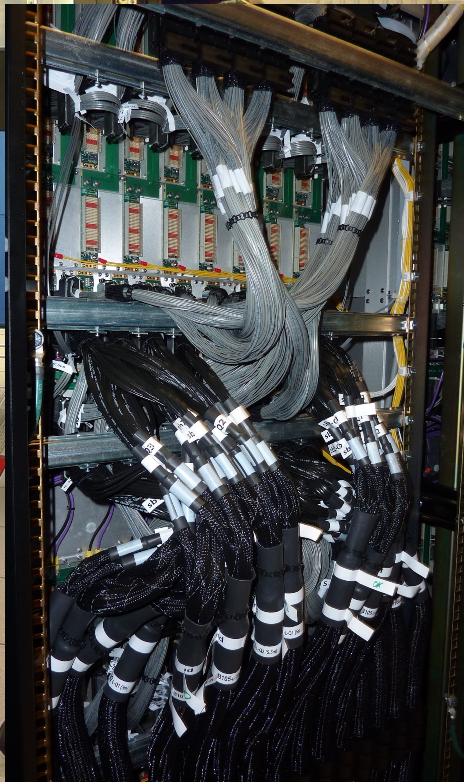
S2 LBI Correlator:
Employed VHS tapes



WIDAR

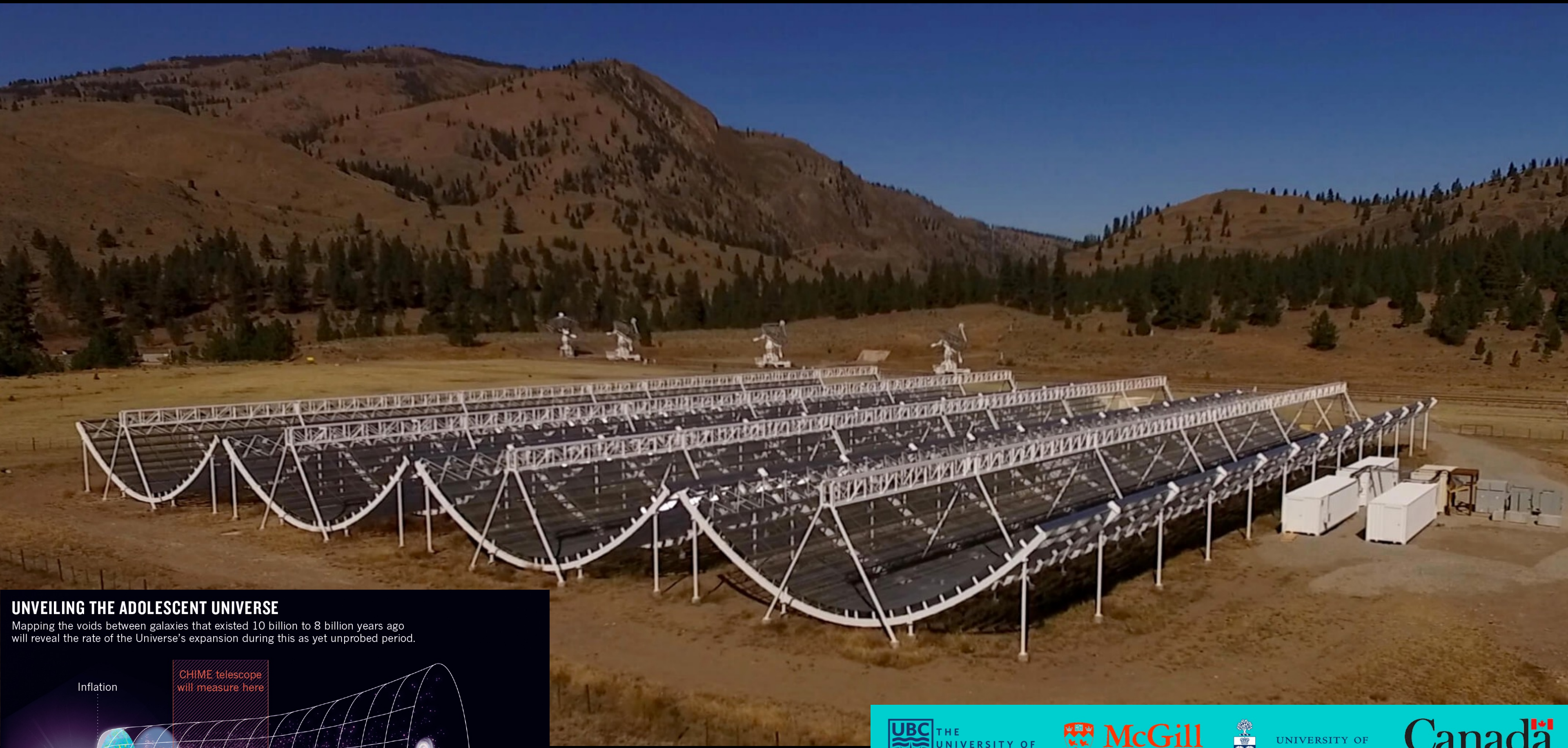


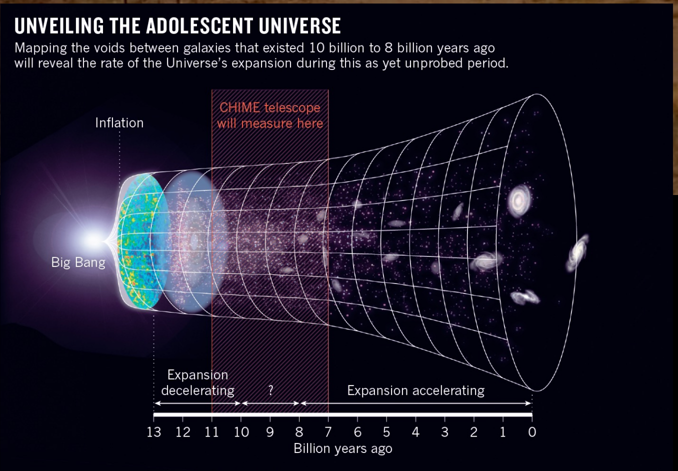

National Radio Astronomy
OBSERVATORY
VERY LARGE ARRAY
ASSOCIATED UNIVERSITIES, INC
NATIONAL SCIENCE FOUNDATION



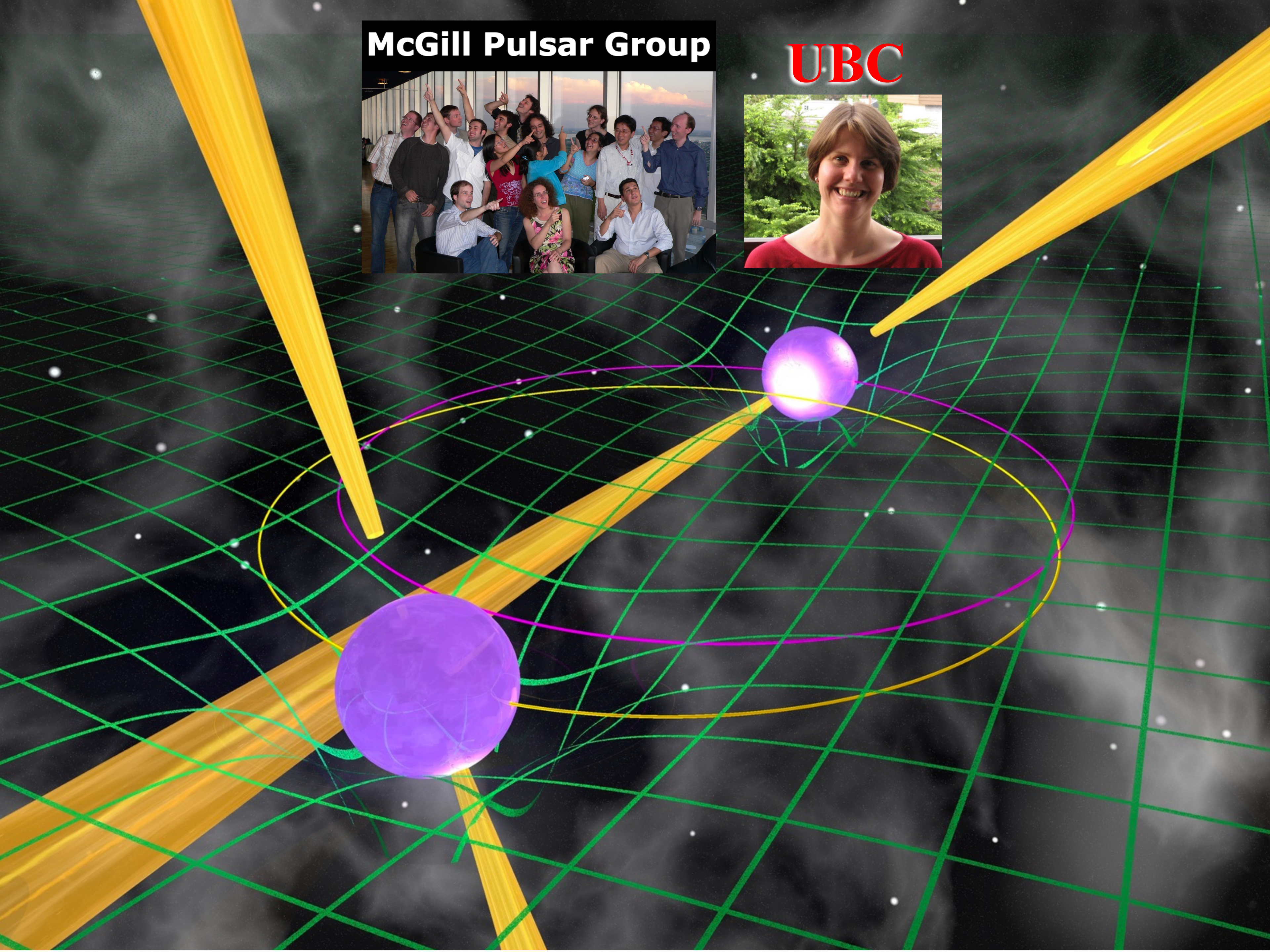
CHIME

The Canadian Hydrogen Intensity Mapping Experiment is a revolutionary new Canadian radio telescope designed to answer major questions in astrophysics & cosmology.

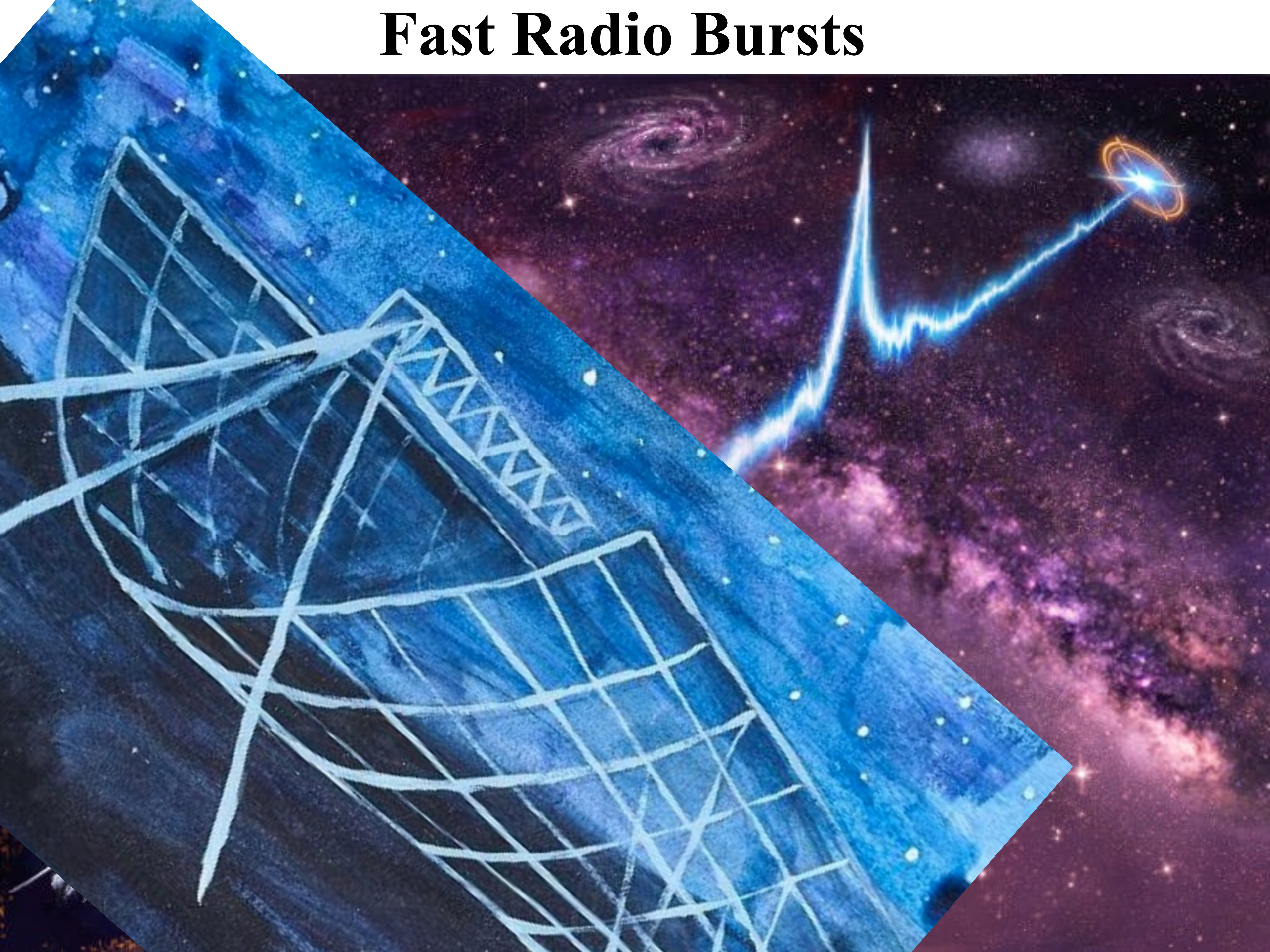




THE UNIVERSITY OF BRITISH COLUMBIA
McGill UNIVERSITY
UNIVERSITY OF TORONTO
Canada NRC·CNRC
Yale University
West Virginia University
PERIMETER INSTITUTE
Carnegie Mellon University
NRAO


McGill Pulsar Group
UBC

Fast Radio Bursts

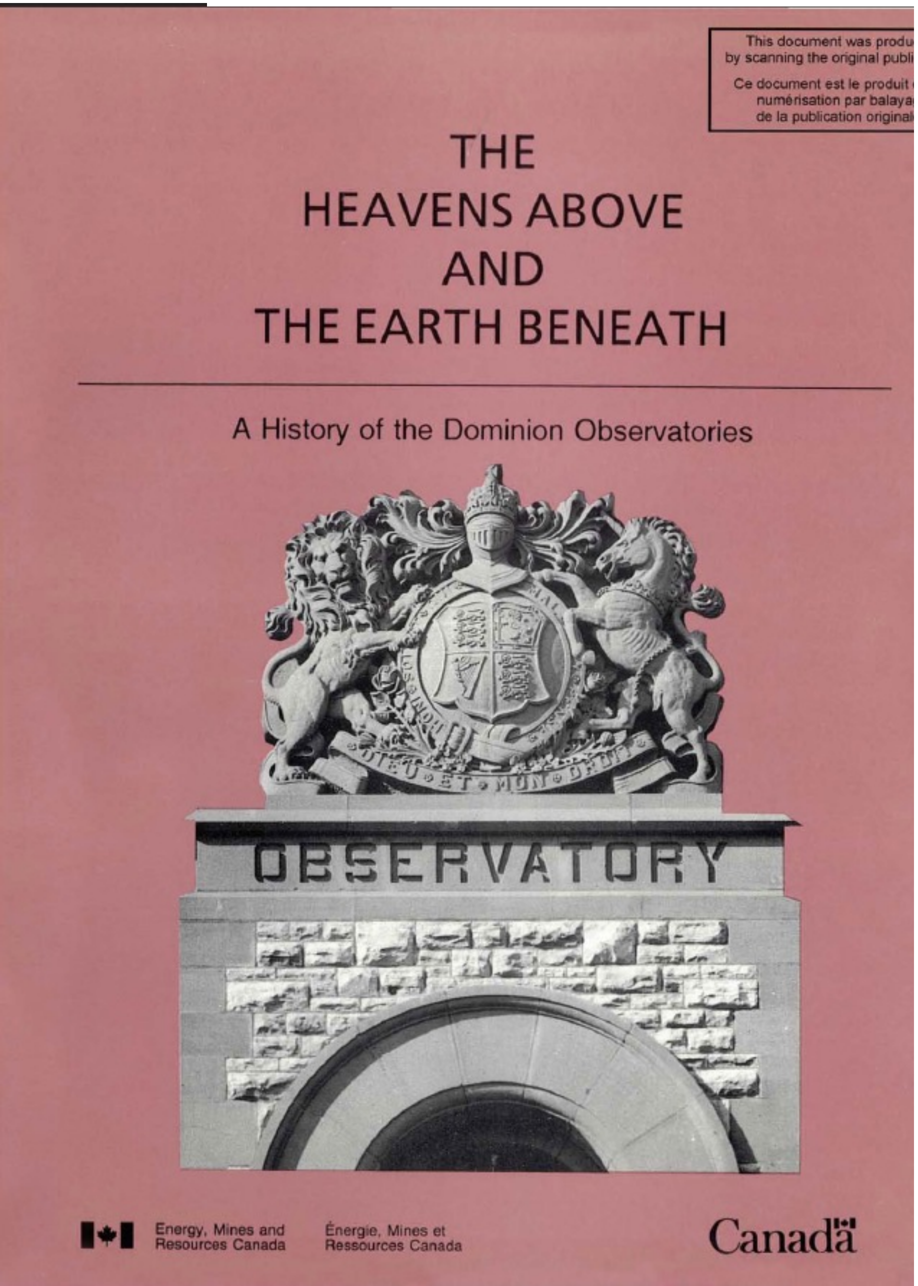


SKA

SQUARE KILOMETRE ARRAY

Next Generation Very Large Array

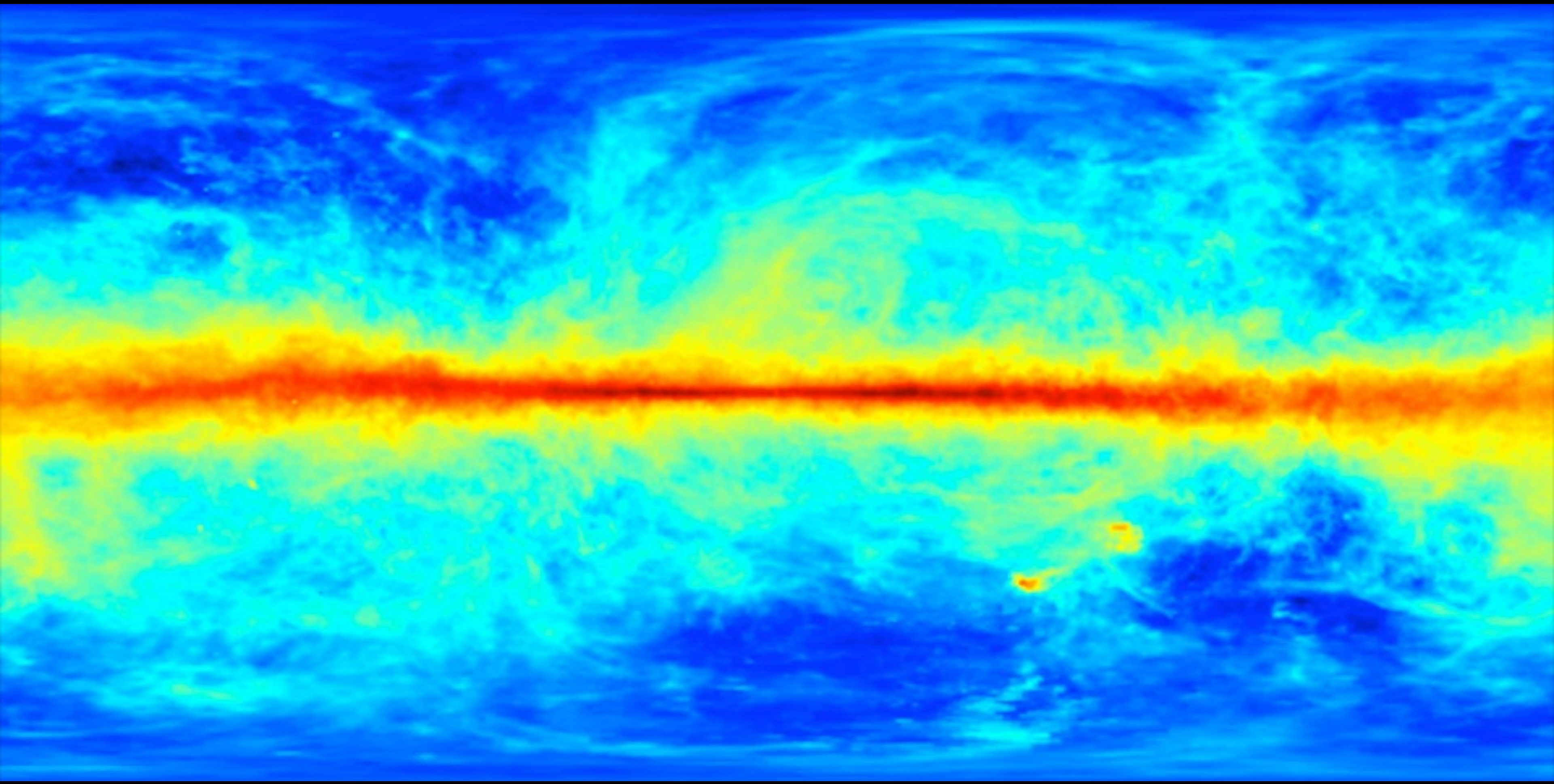
A close-up of the paraboloid. I asked Dr. Galt to give me a photograph showing him at work; this was his contribution.



A Workshop Celebrating the Career of John A. Galt

September 22-23, 2015

John Galt's legacy continues on at the DRAO.



We plan to map 21-cm Zeeman splitting throughout the Milky Way with the 26-m.

ATTEMPTS TO MEASURE THE GALACTIC MAGNETIC FIELD

BY THE ZEEMAN EFFECT

A thesis
submitted to the
Victoria University of Manchester
for the degree of
Doctor of Philosophy
by
Conrad H. Slater
April 1961

AN INVESTIGATION OF ZEEMAN SPLITTING

OF 21 CM ABSORPTION LINES

A thesis
submitted to the
Victoria University of Manchester
for the degree of
Doctor of Philosophy
by
W. L. H. Shuter
January, 1963

21 cm. STUDIES OF THE GALACTIC MAGNETIC FIELD

A thesis
submitted to the
Victoria University of Manchester
for the degree of
Doctor of Philosophy
by
P. A. T. Wild
January 1963

On the Magnetic Fields in the Galaxy

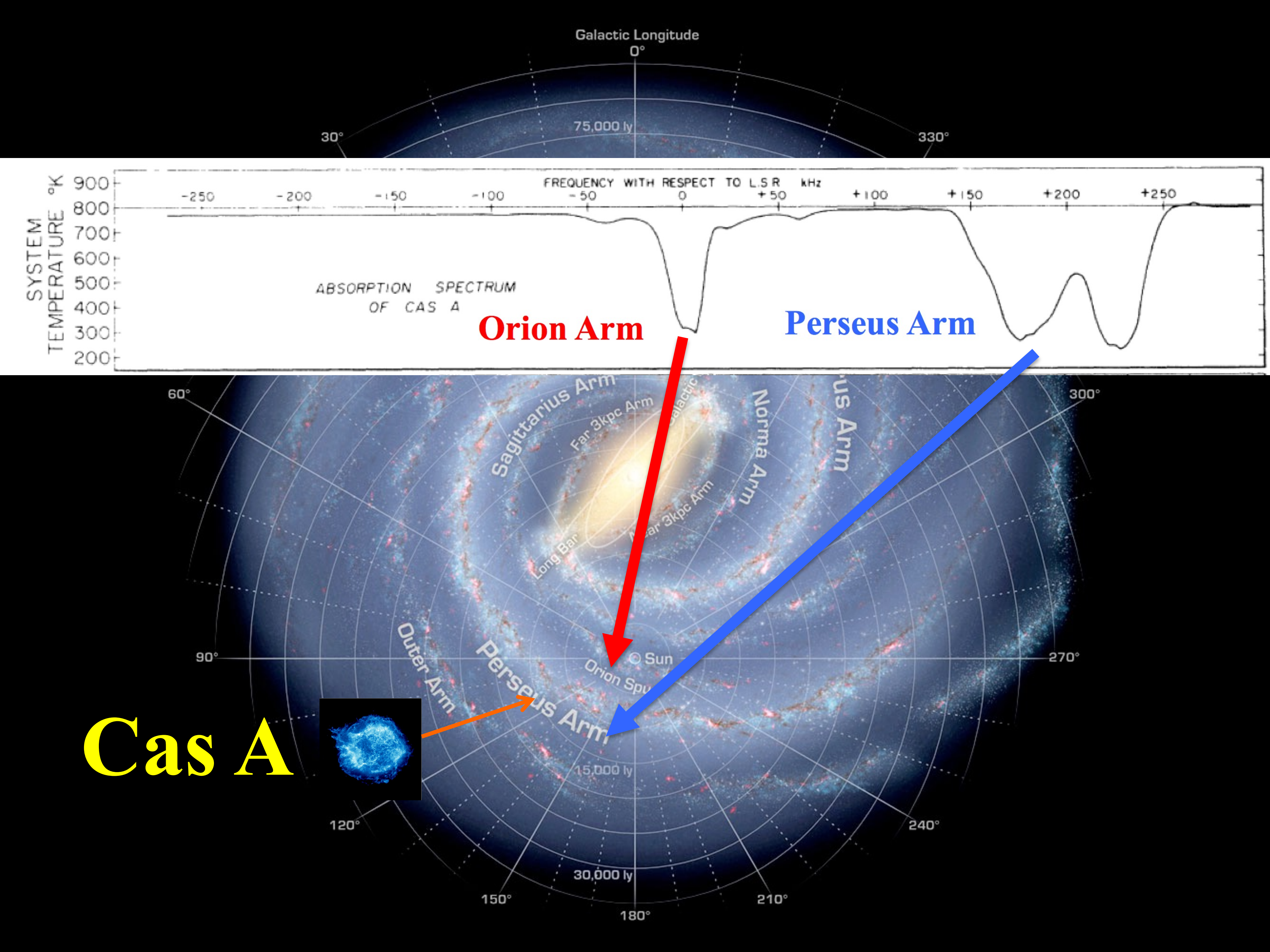
A thesis
submitted to the
Victoria University of Manchester
for the degree of
Doctor of Philosophy
by
Gerrit Laurens Verschuur
April 1965

Rod Davies
(1930-2015)

Ten years go by at Jodrell Bank with thousands of hours of telescope time spent looking for 21-cm Zeeman effect.
No detections.

Meanwhile, Sandy Weinreb uses NRAO 85-ft in Green Bank to look for 21-cm Zeeman effect.
No detections.

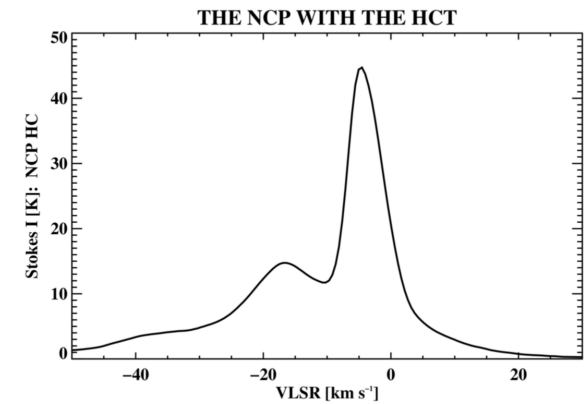
Meanwhile, a Caltech group at Owens Valley looks for 21-cm Zeeman effect.
No detections.

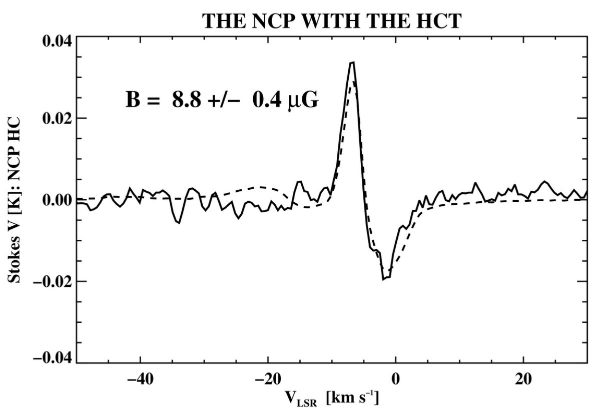

Galactic Longitude
0°
30°
330°
75,000 ly
SYSTEM TEMPERATURE °K
900
800
700
600
500
400
300
200
FREQUENCY WITH RESPECT TO L.S.R. kHz
-250
-200
-150
-100
-50
0
+50
+100
+150
+200
+250
ABSORPTION SPECTRUM OF CAS A
Orion Arm
Perseus Arm
60°
300°
Sagittarius Arm
Far 3kpc Arm
Norma Arm
Near 3kpc Arm
Long Bar
90°
270°
Sun
Orion Spur
Outer Arm
Perseus Arm
Cas A
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

The Zeeman Effect

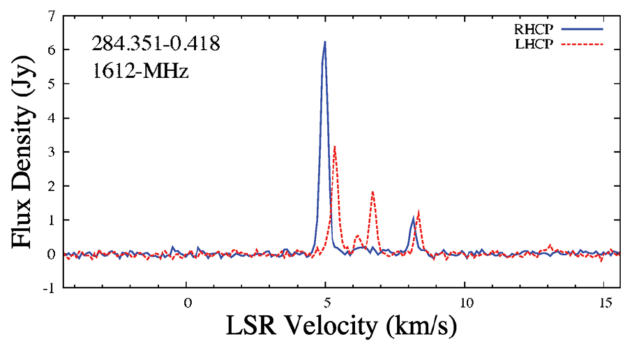
Magnetic fields leave a fingerprint on the circular polarization of certain spectral lines from interstellar gas. Radio spectral lines from 800-1800 MHz:

1420 MHz Hydrogen Line
a.k.a. “The 21-cm Line”



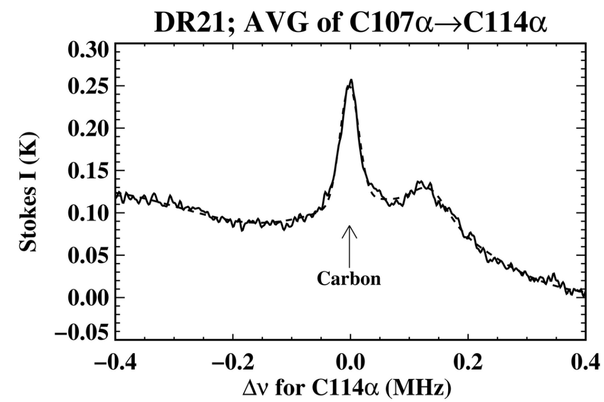


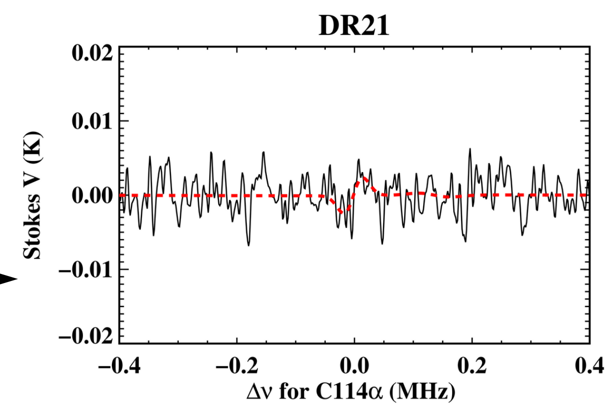
1612, 1665/1667, 1720 MHz Hydroxyl Lines



OH masers are so narrow, they can be fully split and yield total B field.

40 Hydrogen Radio Recombination Lines
40 Helium Radio Recombination Lines
40 Carbon Radio Recombination Lines





← **RCP - LCP** →

POSITIVE DETERMINATION OF AN INTERSTELLAR MAGNETIC FIELD BY MEASUREMENT OF THE ZEEMAN SPLITTING OF THE 21-cm HYDROGEN LINE

G. L. Verschuur
National Radio Astronomy Observatory,* Green Bank, West Virginia
(Received 17 July 1968) 9 Years & 2 Weeks

Fields of the order of 2×10^{-5} G exist in the Perseus spiral arm in the direction of the radio source Cassiopeia A.

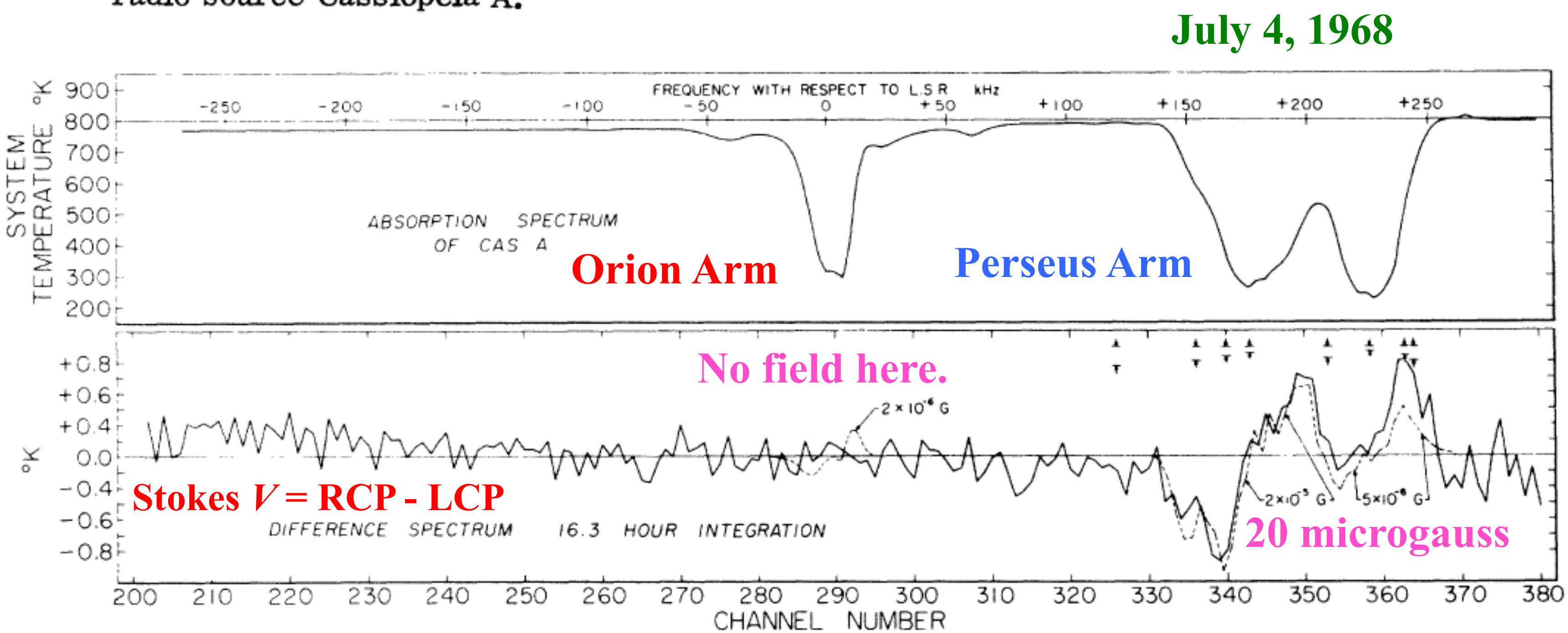
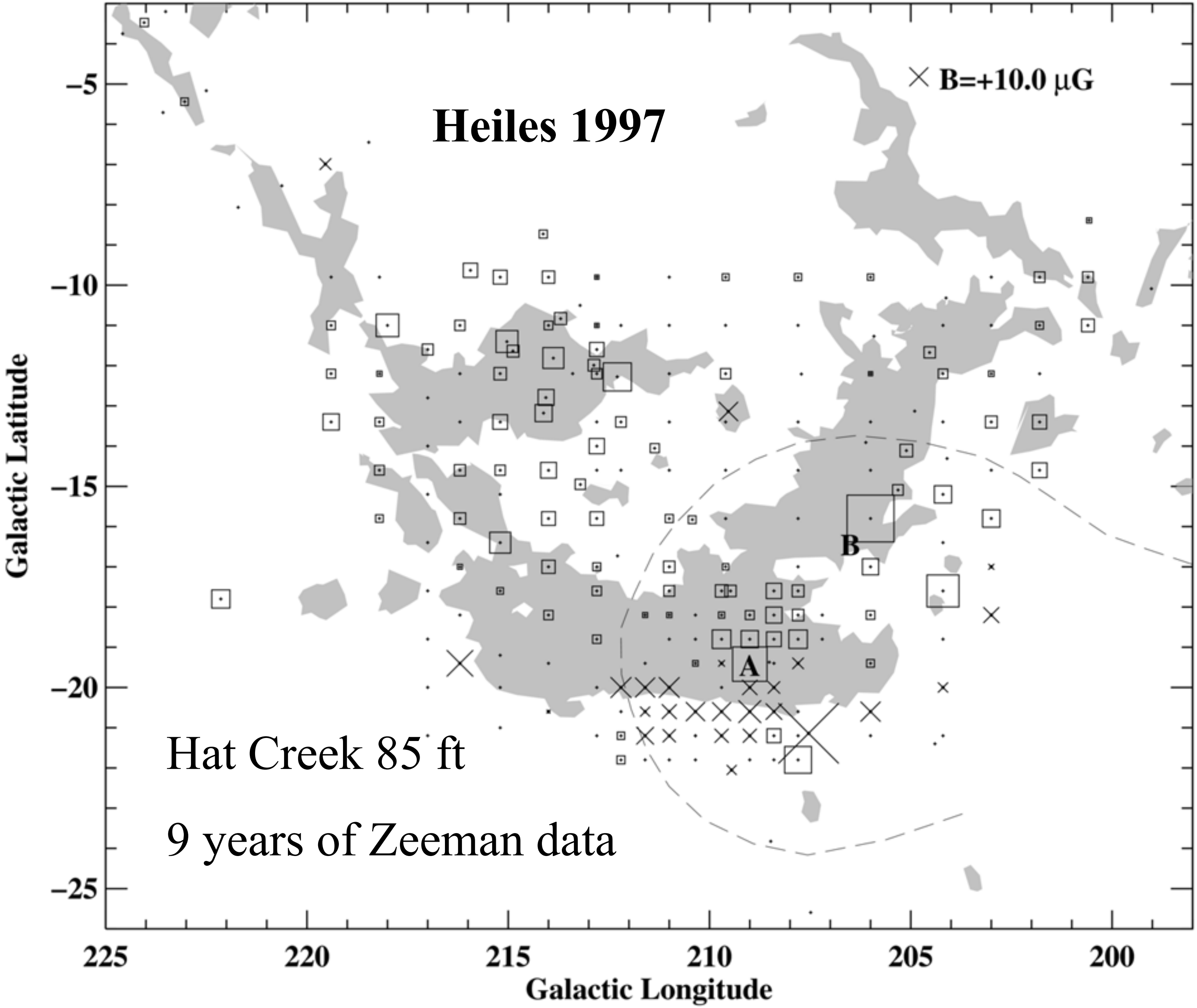


FIG. 1. The absorption spectrum of Cas A, together with the difference spectrum, right-hand minus left-hand polarization, incident on the feed representing 16.3 h of integration. Frequencies with respect to the local standard of rest are indicated. Arrowed bars represent expected peak-to-peak noise at various parts of the spectrum.



× B=+10.0 μG
Heiles 1997
Hat Creek 85 ft
9 years of Zeeman data
A
B
Galactic Latitude
Galactic Longitude
−5
−10
−15
−20
−25
225
220
215
210
205
200

L204: A GRAVITATIONALLY CONFINED DARK CLOUD IN A STRONG MAGNETIC ENVIRONMENT

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Received 1987 April 10; accepted 1987 June 26

27

ABSTRACT

L204 is a filamentary dark cloud located in the H I expanding shell associated with the North Polar Spur. We have measured the magnetic field strength in the surrounding H I from Zeeman splitting of the 21 cm line. The average line-of-sight component of magnetic field, $B_{\|}$, in the H I is 4.2 μG. Using the observed tendency for $B_{\|}$ and the H I velocity to correlate, we argue that variations in $B_{\|}$ result primarily from projection effects, that the total field strength in the H I is $\sim$12 μG, and that magnetic pressure dominates gas pressure. We argue that Alfvén waves might be responsible for the observed tendency for $B_{\|}$ and the H I line width to be anticorrelated. We estimate the field strength in the molecular portion of L204 itself and argue that the small enhancement found within the dense filament is consistent with theoretical expectation. Magnetic braking should have occurred for the component of rotation perpendicular to the magnetic field.

MAGNETIC FIELDS, PRESSURES, AND THERMALLY UNSTABLE GAS IN PROMINENT H I SHELLS

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Received 1988 April 8; accepted 1988 June 28

73

ABSTRACT

We have measured $B_{\|}$ using the Zeeman effect for the 21 cm line in emission for 73 positions located both in morphologically distinct H I shells and in a comparison region. The H I structures are filamentary instead of sheetlike. $B_{\|}$ is typically $\sim$6.4 μG in morphologically prominent filaments and smaller elsewhere. In the filaments, magnetic pressure dominates thermal and turbulent gas pressures by factors of $\sim$67 and $\sim$10, respectively, if our estimates of H I volume density are correct; line widths are typically $\sim$1.8 times smaller than the Alfvén velocity. The magnetic pressure $B^2/8\pi \sim 4.7 \times 10^4$ cm^{-3} K. $B_{\|}$, as derived from the Zeeman effect, does not correlate with Faraday rotation.

In the process of deriving $B_{\|}$, we decomposed the H I spectrum for every position into Gaussian components. Most positions require a broad Gaussian, which presumably corresponds to the "warm neutral medium." Full widths at half-maximum for many of these broad components imply temperatures less than a few thousand K, much smaller than the average FWHM for broad components. Gas at such temperatures is thermally unstable.

THE MAGNETIC FIELD IN THE OPHIUCHUS DARK CLOUD COMPLEX

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Received 1993 June 21; accepted 1993 September 22

52

ABSTRACT

By searching for the Zeeman effect in 21 cm H I spectra taken at 52 positions across the face of the Ophiuchus dark cloud complex, we have mapped out the strength of the line-of-sight magnetic field in the atomic gas associated with the complex.

The H I line profiles are comprised of multiple components, which are identified as arising from different physical regimes along the line of sight. A technique known as "Gaussianizing" is used to fit an independent field strength to each velocity component in each spectrum. The components with LSR velocities closest to the molecular gas in Ophiuchus are typically seen in self-absorption, as is to be expected if the H I giving rise to this component is indeed associated with relatively cold (i.e., molecular) gas. Thus, we take the field in the self-absorption component of the H I to be most representative of the dark cloud complex.

Using the line-of-sight field strengths measured via detection of the Zeeman effect in the H I self-absorption component, and optical polarization data which describe the plane-of-the-sky field structure, we present a model for the three-dimensional structure of the magnetic field near L1688. We estimate the mean uniform field for this region to be 10.2 μG, with an inclination to the line-of-sight of 32°. If there are four correlation lengths of the field along the line of sight, and the fluctuating component of the field is isotropic in three dimensions, then the typical strength of the nonuniform field is $\sim$6 μG, and the ratio of energy in the nonuniform and uniform field is of order unity.

OBSERVATIONS OF MAGNETIC FIELDS IN DIFFUSE CLOUDS

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Received 1994 April 8; accepted 1994 September 26

60

ABSTRACT

We report 32 statistically significant measurements of the line-of-sight component of the magnetic field strength, B_z, in four diffuse clouds, via the Zeeman effect in the 21 cm line of H I. The region near MBM 27–30 in the Ursa Major complex has $B_z > 4$ μG throughout a filamentary region 15 pc long, with significant structure on scales as small as 1.6 pc. The greatest field strength measured in this cloud is 19 ± 2 μG, greater than in most diffuse clouds by a factor $\sim$2. Comparison of measurements with different telescopes suggests that the field strength at the map peak may be significantly greater than 19 μG on scales smaller than 1.6 pc. The magnetic and kinetic energy densities **M** and **K** in this cloud are comparable, within a factor 2 of 2×10^{-11} ergs cm^{-3}, and greater than the gravitational energy density by a factor $\sim$500. Among the four clouds surveyed, six positions where CO emission is a local maximum have essentially the same mean line-of-sight field strength, $B_z \approx 8$ μG, as do four positions where CO emission is too weak to be detected The similarity of **M** and **K** in the diffuse clouds discussed here, as well as in denser, self-gravitating clouds, suggests strong coupling between magnetic fields and gas motions in some interstellar clouds, independent of their self-gravity. This coupling probably arises from ion-neutral collisions, which allow propagation of MHD waves.

A HOLISTIC VIEW OF THE MAGNETIC FIELD IN THE ERIDANUS/ORION REGION

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Received 1996 July 8; accepted 1997 January 17

217

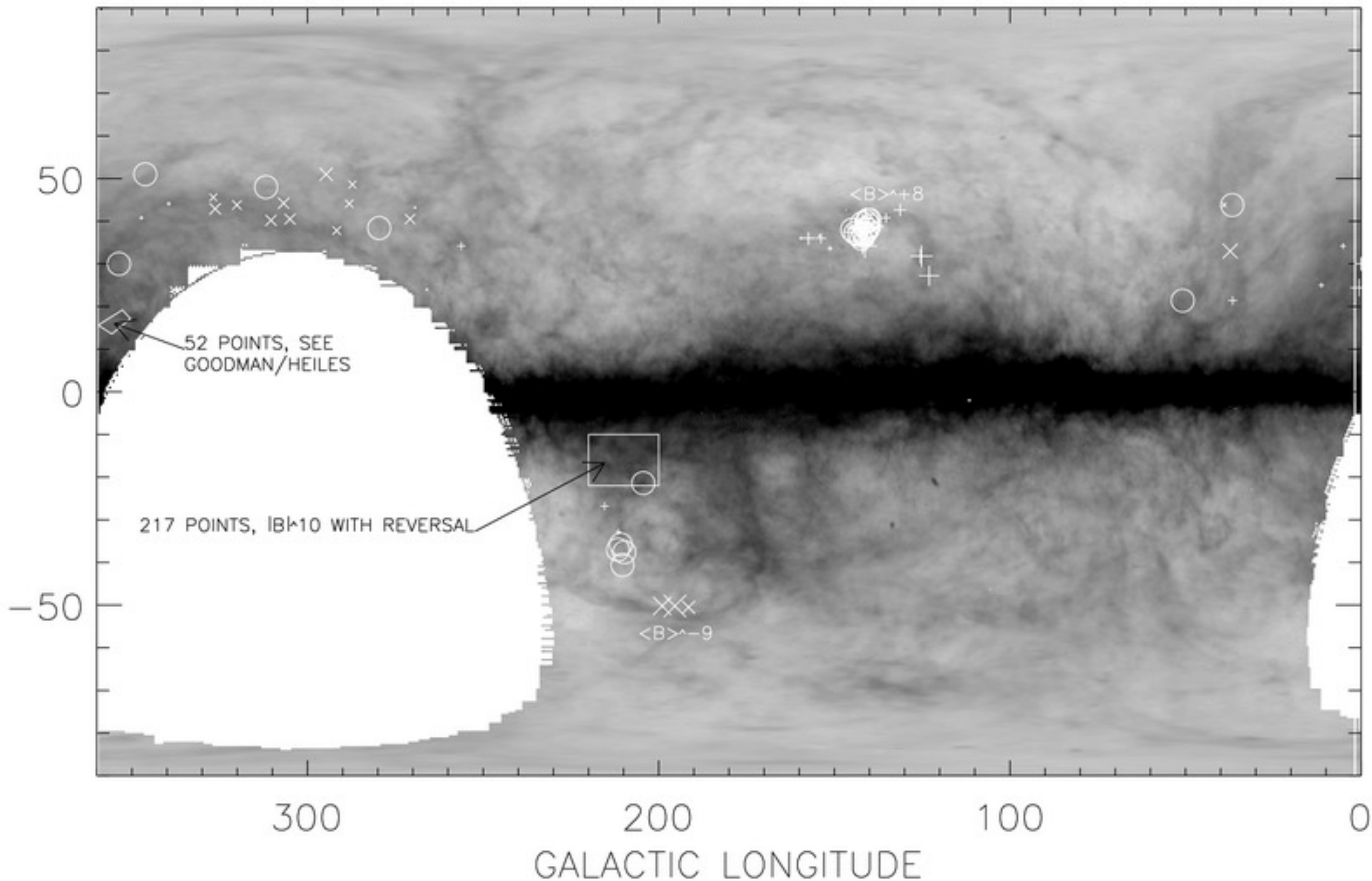
ABSTRACT

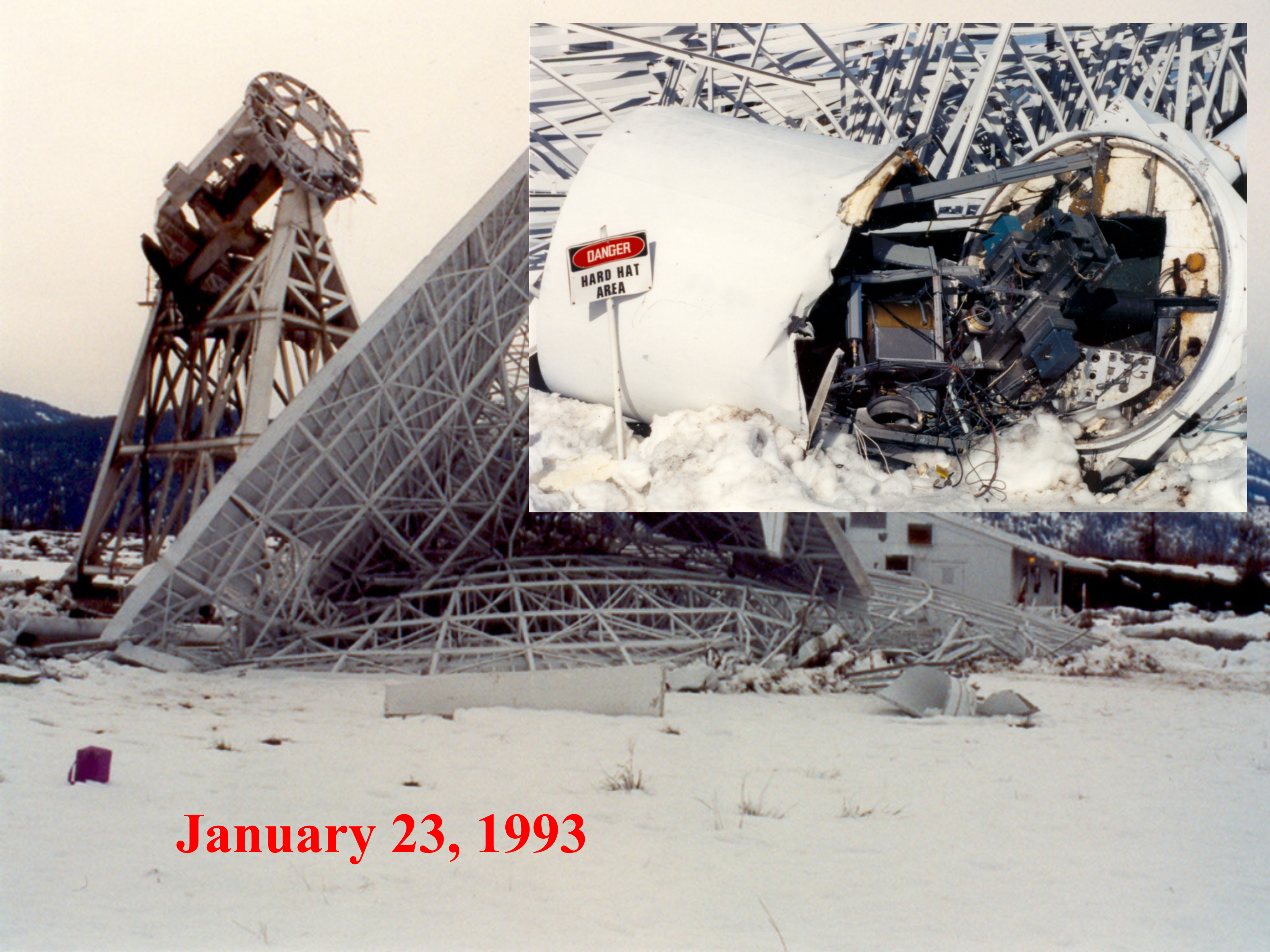
We present observations of 21 cm emission-line Zeeman splitting at 217 positions in the Orion/Eridanus loop region and incorporate them with stellar polarization data in a partially successful attempt to develop a holistic interpretation of the magnetic field structure on small and large size scales. We develop the "paraboloidal model" to describe the idealized perturbation to ambient magnetic field lines expected for a worm/chimney structure. We compare the magnetic field data to this model and find fair agreement for part of the region. On the small scale of one of the molecular clouds, previous interpretations invoke a helical field; in contrast, our interpretation invokes the Eridanus shock and its interaction with dense molecular clouds, in which the observed reversal in the line-of-sight field occurs naturally.

1987 to 1997:

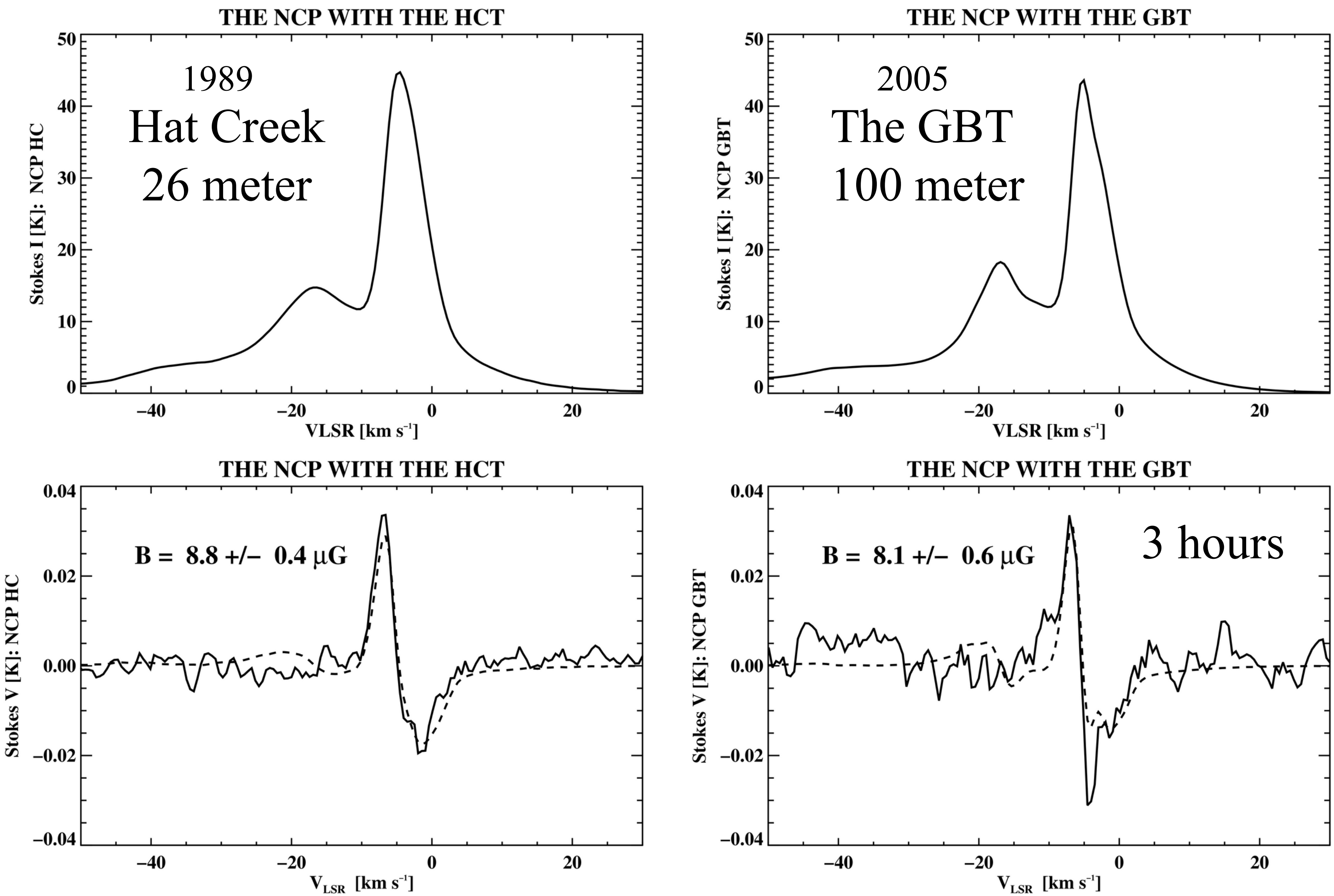
Total = 429 positions

Magnetic Fields Measured in 400+ positions

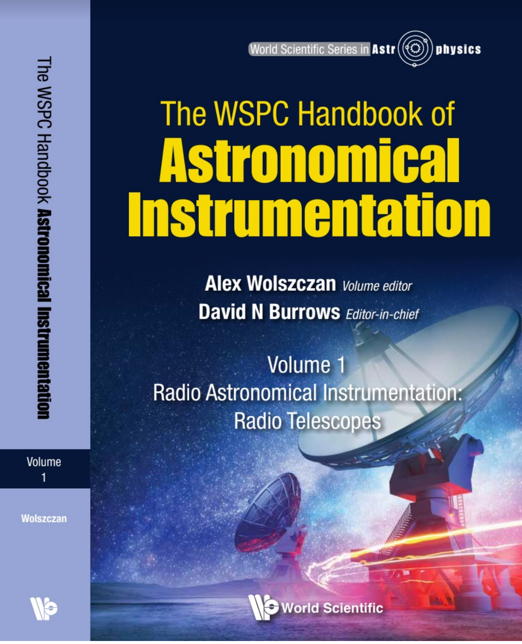




January 23, 1993



THE NCP WITH THE HCT
1989
Hat Creek
26 meter
Stokes I [K]: NCP HC
VLSR [km s⁻¹]
THE NCP WITH THE GBT
2005
The GBT
100 meter
Stokes I [K]: NCP GBT
VLSR [km s⁻¹]
THE NCP WITH THE HCT
B = 8.8 +/− 0.4 μG
Stokes V [K]: NCP HC
V_LSR [km s⁻¹]
THE NCP WITH THE GBT
B = 8.1 +/− 0.6 μG
3 hours
Stokes V [K]: NCP GBT
V_LSR [km s⁻¹]



Astrophysics > Instrumentation and Methods for Astrophysics

The Measurement of Polarization in Radio Astronomy

Timothy Robishaw, Carl Heiles

(Submitted on 19 Jun 2018)

Modern dual-polarization receivers allow a radio telescope to characterize the full polarization state of incoming interstellar radio waves. Many astronomers incorrectly consider a polarimeter to be the "backend" of the telescope. We go to lengths to dissuade the reader of this concept: the backend is the least complicated component of the radio telescope when it comes to measuring polarization. The feed, telescope structure, dish surface, coaxial cables, optical fibers, and electronics can each alter the polarization state of the received astronomical signal. We begin with an overview of polarized radiation, introducing Jones and Stokes vectors, and then discuss construction of digitized pseudo-Stokes vectors from the outputs of modern correlators. We describe the measurement and calibration process for polarization observations and illustrate how instrumental polarization can affect a measurement. Finally, we draw attention to the confusion generated by various polarization conventions and highlight the need for observers to state all adopted conventions when reporting polarization results.

Comments: 32 pages, 7 figures. Chapter to appear in 2019 in The WSPC Handbook of Astronomical Instrumentation, Volume 1, Radio Astronomical Instrumentation: Radio Telescopes. Volume edited by Alex Wolszczan and editor-in-chief David N. Burrows
Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:1806.07391 [astro-ph.IM]
(or arXiv:1806.07391v1 [astro-ph.IM] for this version)

Submission history

From: Timothy Robishaw [view email]
[v1] Tue, 19 Jun 2018 18:00:00 UTC (2,217 KB)

Bryan Gaensler is with **Tim Robishaw**.
Admin · June 21

Essential new must-read from Tim and Carl!

(2) Stokes Q is the difference in intensities between horizontal and vertical linearly polarized components and is a measure of the tendency of the radio wave to prefer the horizontal direction. If $Q > 0$ there is an excess of polarized radiation along the horizontal, while for $Q < 0$, there is a vertical excess (Fig. 1b). $Q \equiv I_{0°} - I_{90°}$.
(3) Stokes U is the difference in intensities between linearly polarized components at $+45°$ and $-45°$ and represents the preference of the light to be aligned at $+45°$, with $U < 0$ meaning an excess in linear polarization at an angle $-45°$ to the horizontal (Fig. 1c). $U \equiv I_{+45°} - I_{-45°}$.
(4) Stokes V is the difference between the intensities of the RCP and LCP components and describes the preference for the light to be RCP. For positive Stokes V, there is an excess of RCP over LCP when using the IEEE and IAU conventions (see Sec. 6.2) (Fig. 1d)). $V \equiv I_{\rm RCP} - I_{\rm LCP}$.

It's important to note that these are *definitions*. Stokes himself[11] used the notation $\{A, B, C, D\}$ a century before Chandrasekhar[12] settled on $\{I, Q, U, V\}$, the latter three letters of which were assigned with no motivation. Given Chandrasekhar's convention, there still remains room for ambiguity and confusion: for example, Q could have been defined as $I_{90°} - I_{0°}$, and V could have been defined as $I_{\rm LCP}$ - $I_{\rm RCP}$ (and often is! See Sec. 6).

The degree of polarization, or fractional polarization, is the ratio of the intensity of the polarized emission to the total intensity:

$$p = \frac{I_{\rm pol}}{I_{\rm tot}} = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}; \qquad 0 \le p \le 1 . \tag{7}$$

We can also form fractional linear polarization

$$p_{\rm lin} = \frac{\sqrt{Q^2 + U^2}}{I}; \qquad 0 \le p_{\rm lin} \le 1 , \tag{8}$$

and fractional circular polarization

$$p_{\rm cir} = \frac{V}{I}; \qquad -1 \le p_{\rm cir} \le 1 . \tag{9}$$

When combining (or spatially smoothing) polarized signals, one must combine (or smooth) Stokes parameters, not fractional polarizations, linearly polarized intensities, or polarization angles.[13]

2.3. *Stokes Parameters Expressed in Terms of Electric Fields*

We can also write the Stokes parameters in terms of the time-averaged self- and cross-products of the electric field components as

$$I \equiv \langle E_x \overline{E_x} \rangle + \langle E_y \overline{E_y} \rangle \equiv \langle E_R \overline{E_R} \rangle + \langle E_L \overline{E_L} \rangle , \tag{10a}$$
$$Q \equiv \langle E_x \overline{E_x} \rangle - \langle E_y \overline{E_y} \rangle \equiv \langle E_R \overline{E_L} \rangle + \langle \overline{E_R} E_L \rangle , \tag{10b}$$
$$U \equiv \langle E_x \overline{E_y} \rangle + \langle \overline{E_x} E_y \rangle \equiv -i \left(\langle E_R \overline{E_L} \rangle - \langle \overline{E_R} E_L \rangle \right) , \tag{10c}$$
$$V \equiv -i \left(\langle E_x \overline{E_y} \rangle - \langle \overline{E_x} E_y \rangle \right) \equiv \langle E_R \overline{E_R} \rangle - \langle E_L \overline{E_L} \rangle , \tag{10d}$$

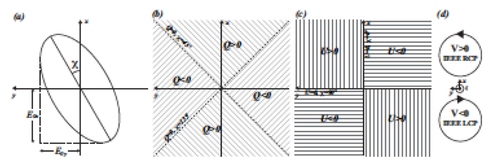


Fig. 1. (*a*) The polarization ellipse. For a radio wave travelling along the z axis (out of the page), the electric field will trace out an ellipse in the xy plane with time at a given position z. The azimuth of the major axis of the ellipse relative to the x axis, χ, is known as the *polarization angle*. IAU convention (see Sec. 6.1) aligns the x axis toward north on the sky. (*b*)-(*c*) Representations of the sign for Stokes Q and U, respectively, given the polarization angle of the major axis of the ellipse. (*d*) Representations of the sign of Stokes V using IEEE and IAU conventions (see Sec. 6.2).

where the angle brackets denote a time average of the electric field,[e] and the overbar denotes complex conjugation.[f] By substituting Eq. (3) and Eq. (4) into Eq. (10), we derive the more commonly found representation[g] of the Stokes parameters:

$$I = \langle E_{0x}^2 \rangle + \langle E_{0y}^2 \rangle = \langle E_{0R}^2 \rangle + \langle E_{0L}^2 \rangle , \tag{11a}$$
$$Q = \langle E_{0x}^2 \rangle - \langle E_{0y}^2 \rangle = 2\langle E_{0R} E_{0L} \rangle \cos\left(\phi_R - \phi_L\right) , \tag{11b}$$
$$U = 2\langle E_{0x} E_{0y} \rangle \cos\left(\phi_y - \phi_x\right) = 2\langle E_{0R} E_{0L} \rangle \sin\left(\phi_R - \phi_L\right) , \tag{11c}$$
$$V = -2\langle E_{0x} E_{0y} \rangle \sin\left(\phi_y - \phi_x\right) = \langle E_{0R}^2 \rangle - \langle E_{0L}^2 \rangle . \tag{11d}$$

From Eq. (11) and Eq. (5), it can be seen that the angle that the polarization ellipse makes with the horizontal (i.e., x axis) can be expressed by

$$\chi = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q} \right) ; \qquad 0° \le \chi \le 180° , \tag{12}$$

where χ is known as the *position angle of linear polarization* (or, more succinctly, the *polarization angle*) and has a total range of 180, not 360, degrees. Therefore, χ

[e] This is necessary because the signal being received is being treated as quasi-monochromatic. Such light will not trace out an ellipse with time, but the ellipse can be recovered if the products are averaged over a time long relative to the period of the radio wave. Even for a very fast correlator that could accumulate only 100 ms of data, there will be millions of wave periods per integration at radio frequencies, which is plenty long to uncover the polarization properties of the astronomical radiation.
[f] Textbooks covering polarization tend to denote complex conjugation as A^*. Many authors reverse terms in some of the difference equations because they've either used the physics convention for Stokes V as IEEE LCP − RCP or they've defined the exponential propagation argument of the E field as the negative of the IEEE convention that we've adopted in Eq. (1). Finally, there is an understood constant on the RHS of each equation accounting for the conversion of the square of the E field to a temperature or flux density.
[g] Optics, radiation, and astronomy texts usually provide this set of Stokes parameters, and will often include their representation as a function of the polarization ellipse parameters. The correlation representation of Eq. (10) is not widely presented.

producing a complex transform of $2N$ channels with Hermitian symmetry having N positive-frequency and N negative-frequency channels. The self-product power spectrum is this FT times its complex conjugate, and because of the Hermitian symmetry, it is real with the N negative- and positive-frequency portions identical. Thus, it is a power spectrum with N independent channels. Similarly, one calculates cross-product power spectra by multiplying the Fourier transforms of the two polarizations with both possibilities of complex conjugate (Eq. (18)). This produces a complex cross-power spectrum having $2N$ independent channels, split between negative and positive frequencies. This cross-power spectrum does not have Hermitian symmetry, so has a real part and an imaginary part, each with N independent channels. Thus, we have four spectra of length N. Symbolically, for the V_A and V_B self-product spectra we write

$$AA = \left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_A)} \right\rangle , \quad BB = \left\langle {\rm FT}(V_B) \overline{{\rm FT}(V_B)} \right\rangle . \tag{15}$$

The FX spectrometer will return either the complex cross-product spectrum

$$\left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_B)} \right\rangle \quad \text{or} \quad \left\langle \overline{{\rm FT}(V_A)} {\rm FT}(V_B) \right\rangle , \tag{16}$$

but not both. Since these are a complex conjugate pair, we can symbolically represent the real and imaginary parts of these cross-product spectra as:

$$\begin{aligned} AB &= {\rm Re} \left\{ \left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_B)} \right\rangle \right\} = \ \ {\rm Re} \left\{ \left\langle \overline{{\rm FT}(V_A)} {\rm FT}(V_B) \right\rangle \right\} , \\ BA &= {\rm Im} \left\{ \left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_B)} \right\rangle \right\} = -{\rm Im} \left\{ \left\langle \overline{{\rm FT}(V_A)} {\rm FT}(V_B) \right\rangle \right\} . \end{aligned} \tag{17}$$

(Note that ambiguity exists in the sign of the BA term because it won't be known a priori which of the cross-product spectra an FX spectrometer will output; this is determined via calibration.) The real-valued Stokes parameter spectra can then be assembled from the self- and cross-product spectra following Eq. (10) as:

$$\begin{aligned} \left[\left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_A)} \right\rangle + \left\langle \overline{{\rm FT}(V_B)} {\rm FT}(V_B) \right\rangle \right] &= AA + BB , \\ \left[\left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_A)} \right\rangle - \left\langle \overline{{\rm FT}(V_B)} {\rm FT}(V_B) \right\rangle \right] &= AA - BB , \\ \left[\left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_B)} \right\rangle + \left\langle \overline{{\rm FT}(V_A)} {\rm FT}(V_B) \right\rangle \right] &= 2\,AB , \\ -i \left[\left\langle {\rm FT}(V_A) \overline{{\rm FT}(V_B)} \right\rangle - \left\langle \overline{{\rm FT}(V_A)} {\rm FT}(V_B) \right\rangle \right] &= 2\,BA . \end{aligned} \tag{18}$$

Even after these self- and cross-products have been properly amplitude-calibrated and combined, they do not provide true Stokes parameters, because the telescope circuitry introduces cross-coupling and phase shifts. Thus, they do not provide a true Stokes vector as defined in Eq. (6) and Eq. (10). Rather, they provide a *pseudo*-Stokes vector with four pseudo-Stokes parameters. In this review, we represent pseudo-Stokes vectors by the special symbol $\mathcal{S}$ (the calligraphic S).

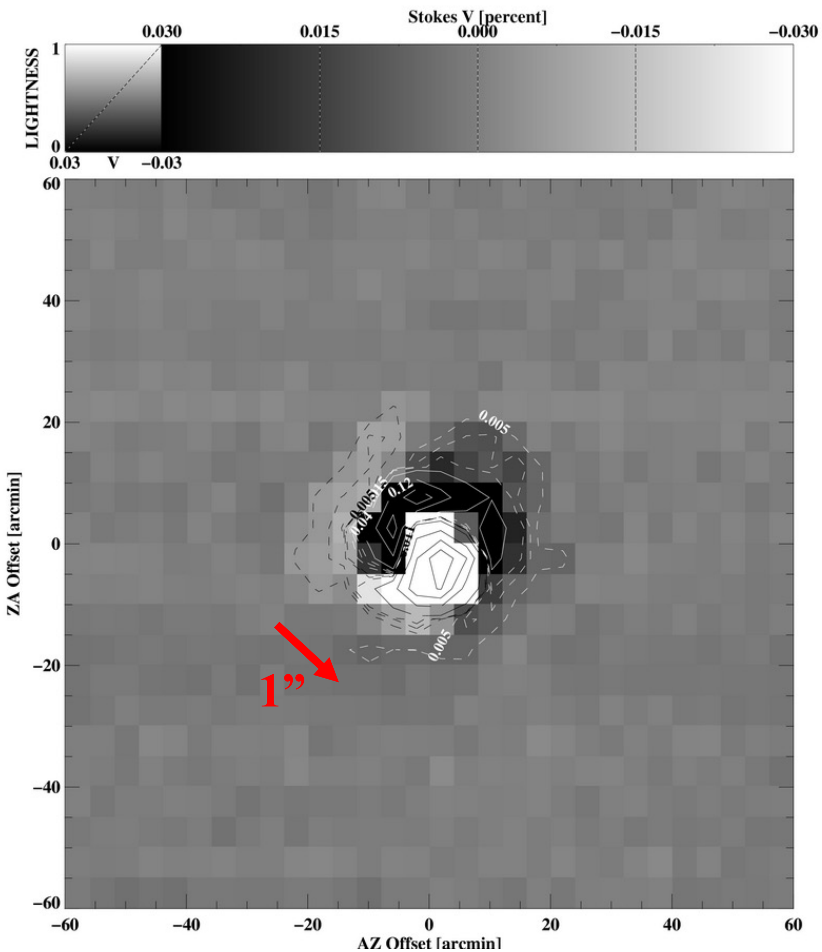
Incorporating all of this, the pseudo-Stokes vector assembled from the correlator output is

$$\mathcal{S}^{\rm cor} = \begin{bmatrix} \mathcal{S}_0^{\rm cor} \\ \mathcal{S}_1^{\rm cor} \\ \mathcal{S}_2^{\rm cor} \\ \mathcal{S}_3^{\rm cor} \end{bmatrix} = \begin{bmatrix} AA + BB \\ AA - BB \\ 2\,AB \\ 2\,BA \end{bmatrix} . \tag{19}$$

Beam Squint

The GBT

Arecibo



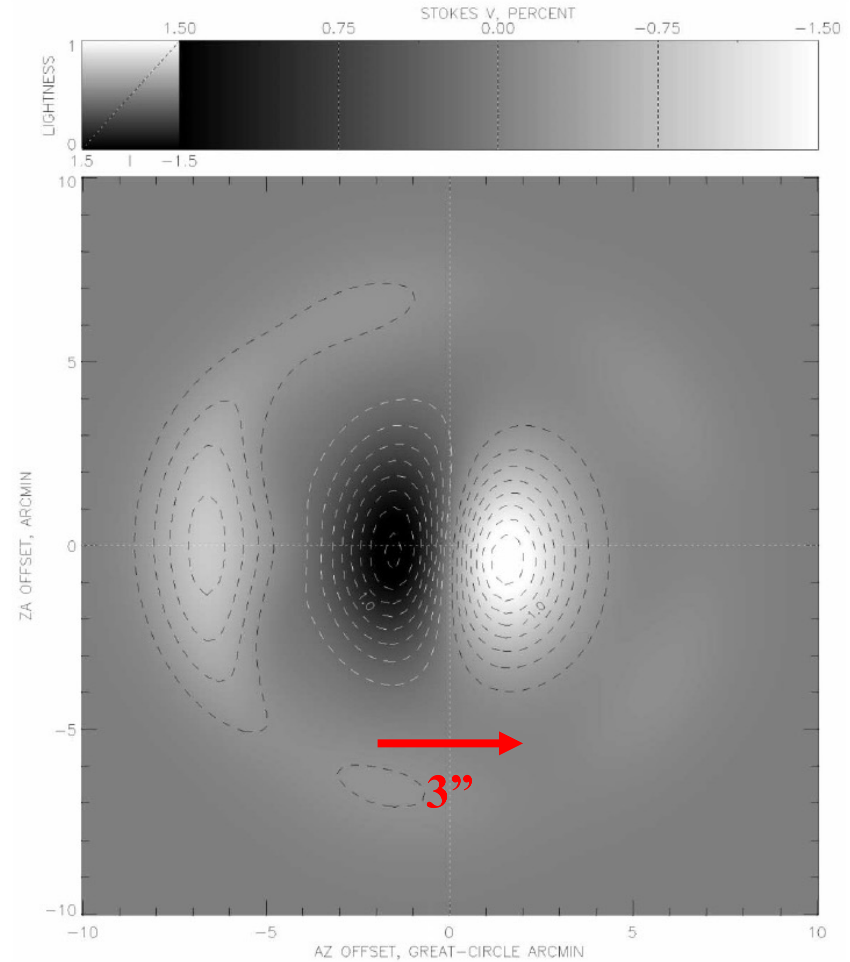
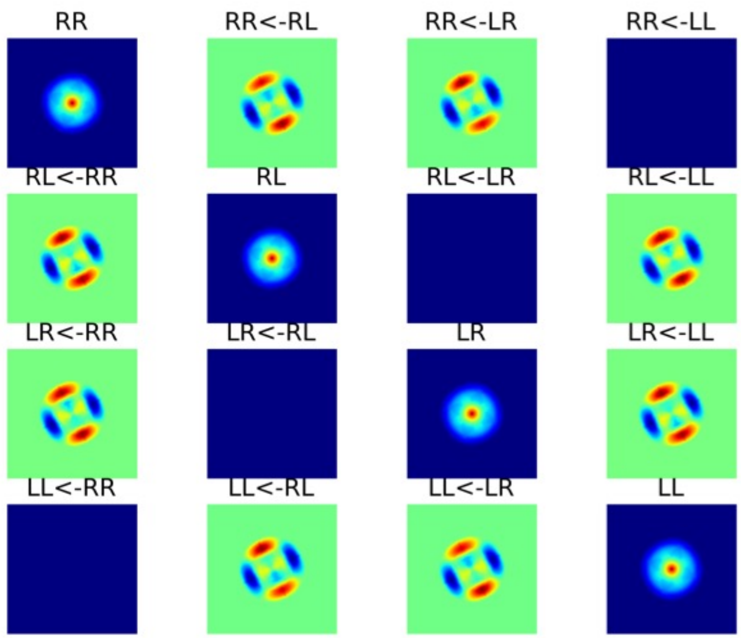
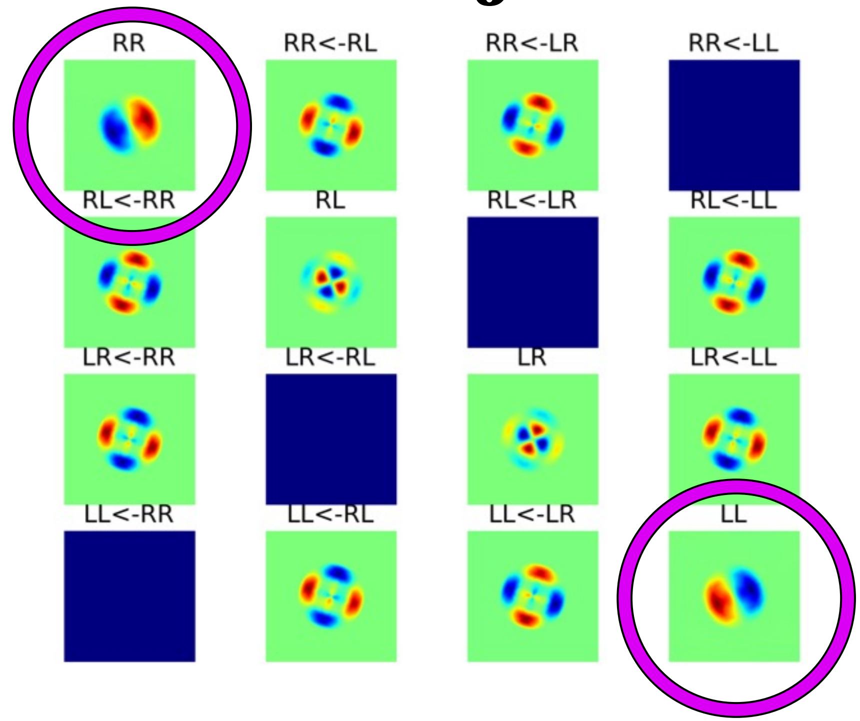


Fig. 18.—Same as Fig. 16 but for Stokes *V*. Contours are spaced by 0.2%; the 0% contour is omitted.

JVLA Full Mueller A-Projection



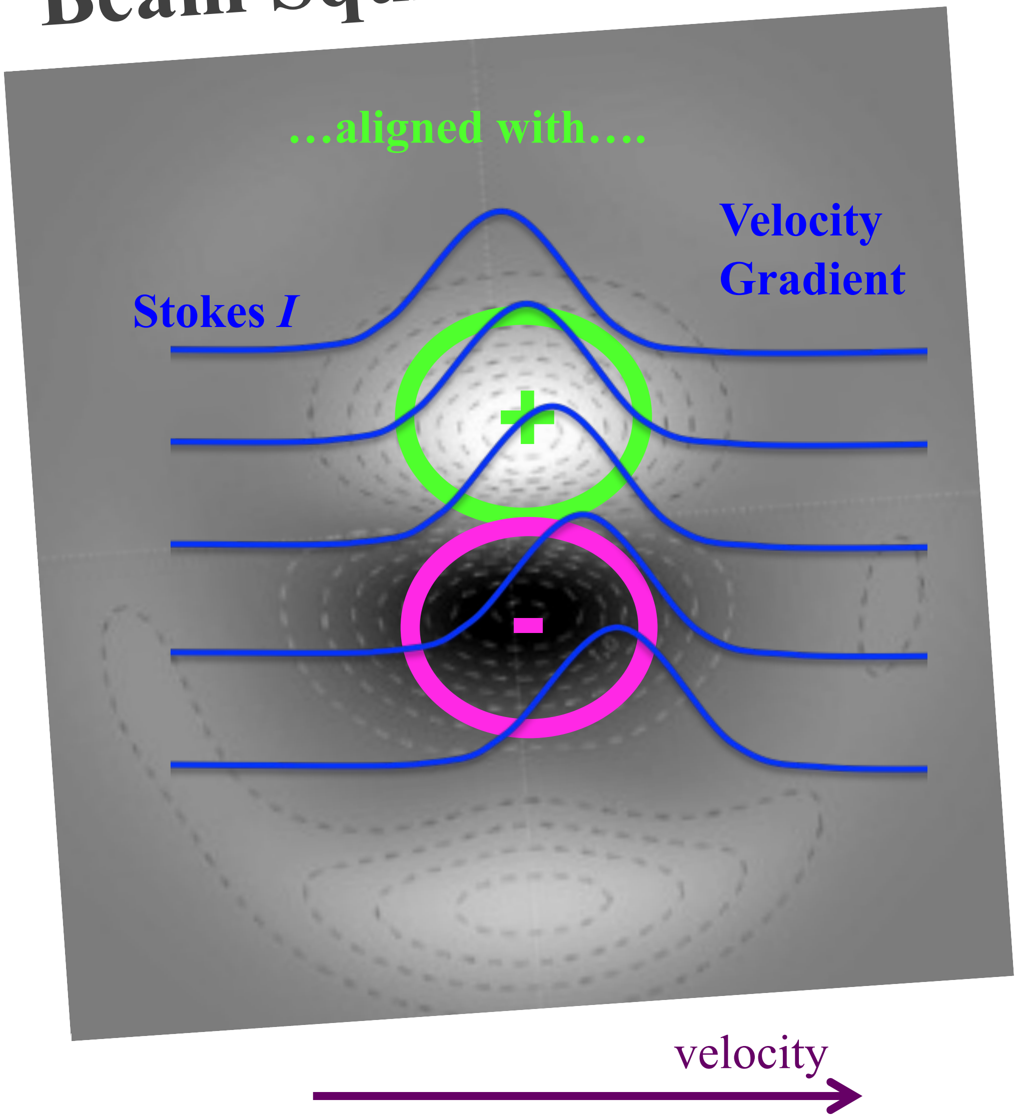
Aperture Real



Aperture Imag

Preshanth Jagannathan (NRAO)

Beam Squint



produces a Stokes *V* response that has the exact signature of Zeeman splitting!

To estimate instrumental contribution we need to know:

(1) Map of beam squint pattern.

(2) Stokes *I* spectral line cube in vicinity of source.

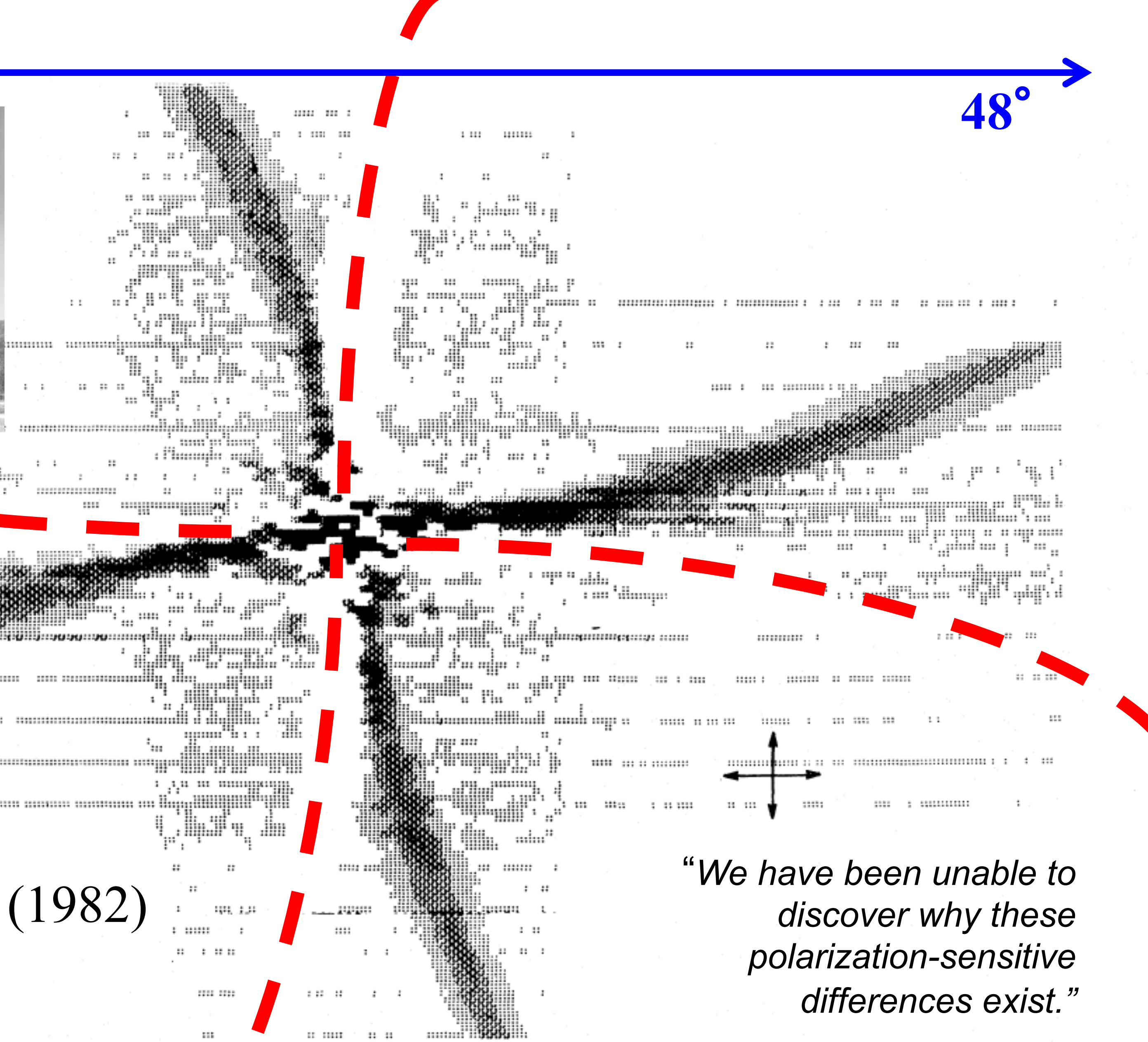


FIG. 1.—Circularly polarized beam pattern of the Hat Creek 26 m telescope within 24° of beam center. Arrows represent 4° in each direction. Only the positive values of the pattern are shown (*dark areas*). Negative values appear in the figure as blank areas.

Troland & Heiles (1982)

"We have been unable to discover why these polarization-sensitive differences exist."

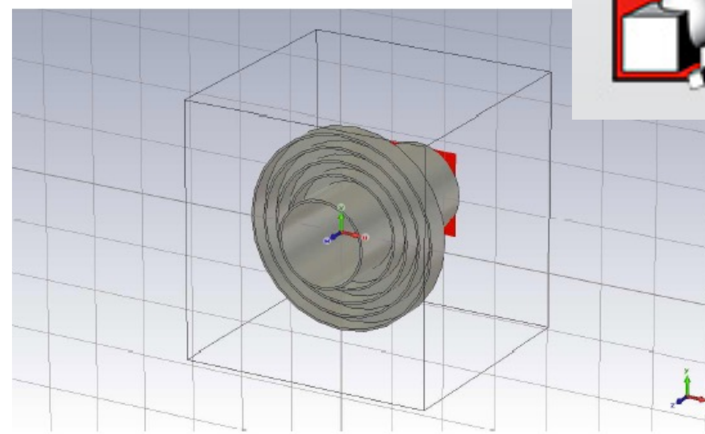
Publications of the Astronomical Society of the Pacific, 128:115006 (16pp), 2016 November
doi:10.1088/1538-3873/128/969/

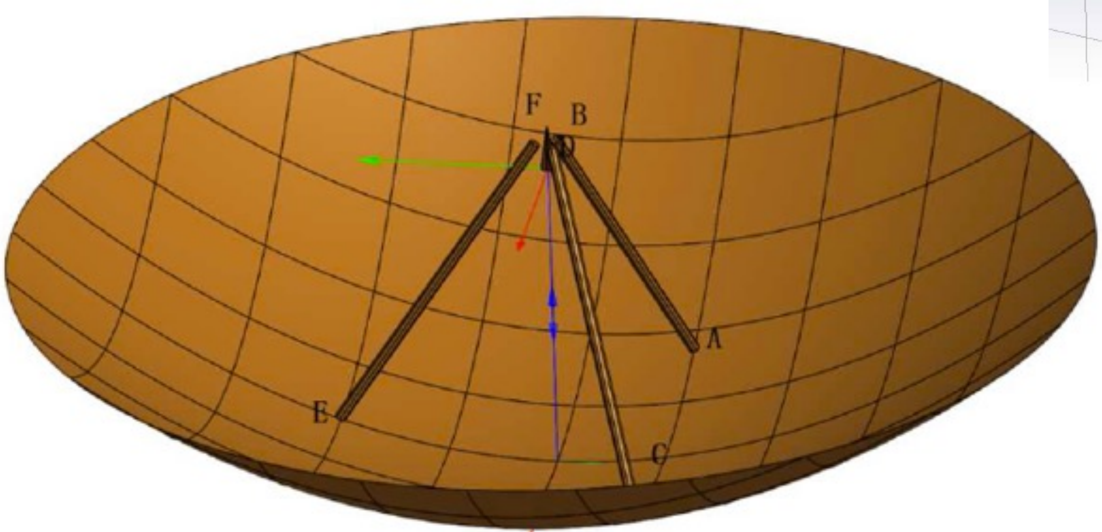
Gain and Polarization Properties of a Large Radio Telescope from Calculation and Measurement: The John A. Galt Telescope

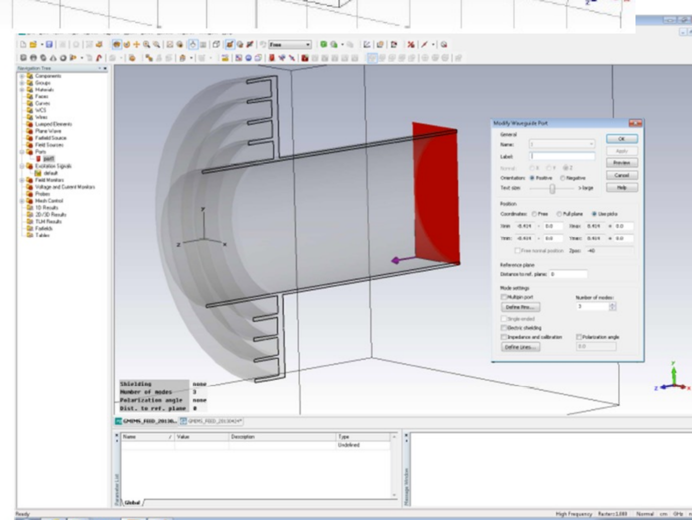
X. Du[1,2,3], T. L. Landecker[1], T. Robishaw[1], A. D. Gray[1], K. A. Douglas[1,4,5], and M. Wolleben[1,6]

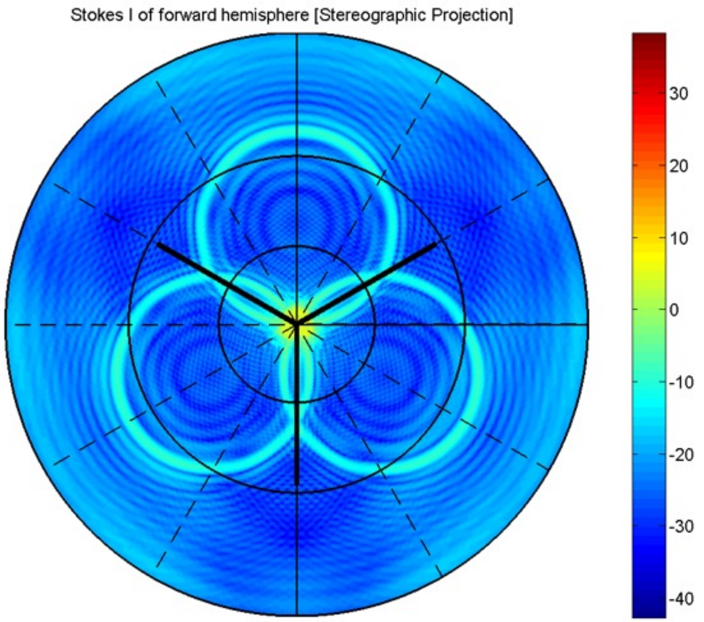
CST – Computer Simulation Technology

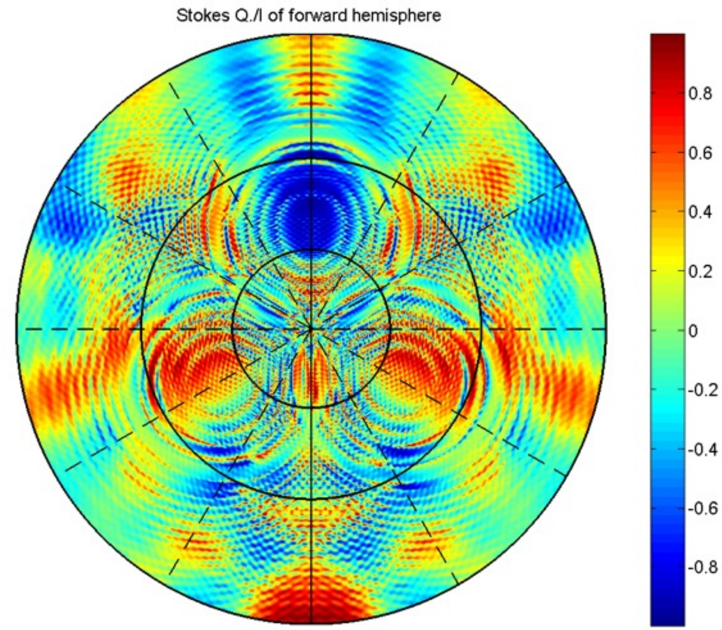
CST MICROWAVE STUDIO®

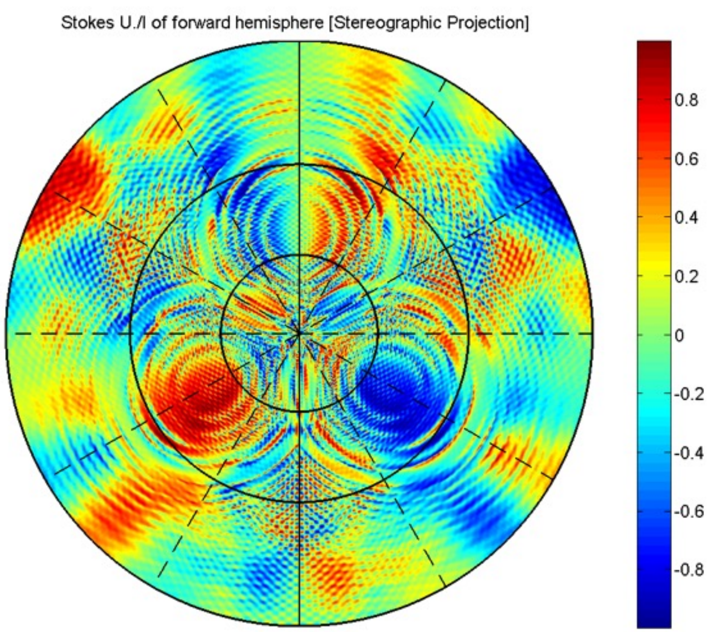


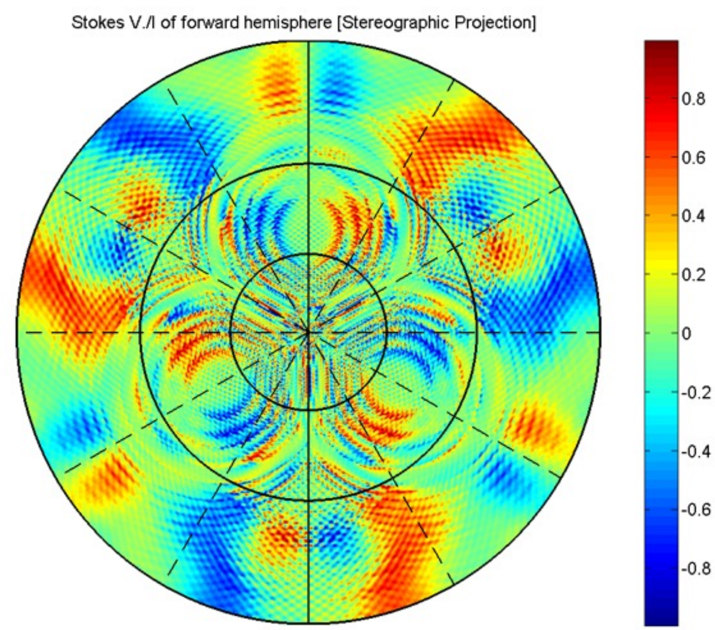


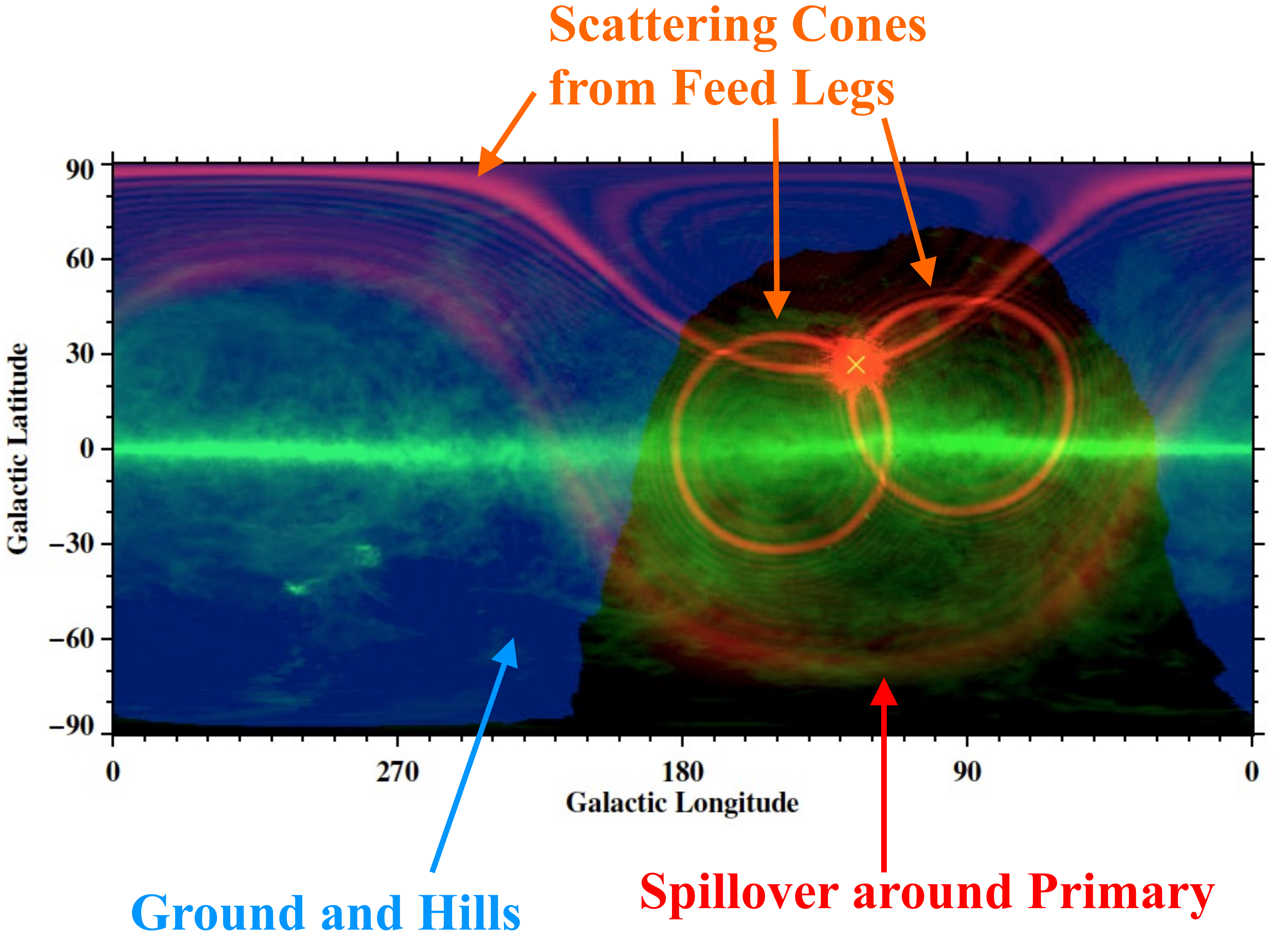



Stokes I of forward hemisphere [Stereographic Projection]
30
20
10
0
-10
-20
-30
-40


Stokes Q./I of forward hemisphere
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8


Stokes U./I of forward hemisphere [Stereographic Projection]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8


Stokes V./I of forward hemisphere [Stereographic Projection]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8


Scattering Cones
from Feed Legs
Galactic Latitude
90
60
30
0
−30
−60
−90
0
270
180
90
0
Galactic Longitude
Ground and Hills
Spillover around Primary

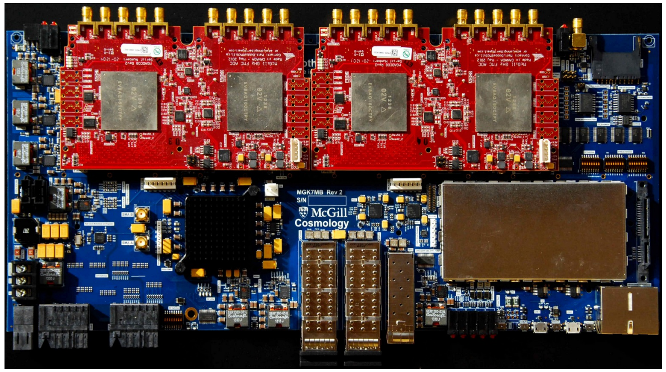
New Eyes

900-1800 MHz

- **World's most sensitive radioastronomical receiver at 1420 MHz.**
- **Specially outfitted with best-performing L-band low-noise amplifiers produced by Frank Jiang at DAO.**

Designed for MeerKAT telescope in South Africa, an SKA pathfinder.

The New Brain



CHIME IceBoard
(Bandura et al. 2016)

- 1420 MHz Hydrogen Line 16,384 channels
- 1612, 1665/1667, 1720 MHz Hydroxyl Lines
  - 65,536 channels each
- 40 Hydrogen Radio Recombination Lines
- 40 Helium Radio Recombination Lines
- 40 Carbon Radio Recombination Lines
  - 40 x 1200 = 48,000 Channels

All exhibit the Zeeman Effect!

Bandwidth of 900 MHz = 20-fold Upgrade!

125 Spectral Lines = 125-fold Upgrade!

9,000,000 Channels = 18,000-fold Upgrade!