A CHRONOLOGICAL HISTORY OF RADIO ASTRONOMY

Notes by W. E. Howard - June 1974

Shortly after joining NRAO in 1964 I delivered a summer student lecture on the history of radio astronomy and developed a short series of notes on the subject that were primarily based on Fred Haddock's excellent historical summary that appeared in the January 1958 issue of the Proceedings of the IRE. Now in 1974 I have the opportunity to deliver an evening public lecture to members of the NRAO staff and families, and the opportunity again presents itself to bring the chronological history up to date. In doing this, I have leaned heavily on J. S. Hey's book, The Evolution of Radio Astronomy (Science History Publications, a division of Neale Watson Academic Publications, Inc., New York 1973) which covers the period up to, and including 1970. Other source material includes the Encyclopedia Britannica Yearbooks, the NRAO reprint series, and the astronomical literature.

This history stresses the observational "firsts" of our science, and I wish to tender my apologies in advance to those observers whose discoveries may have been inadvertently slighted or overlooked. It is particularly difficult to place the most recent advances in proper prospective and future additions must certainly be made to this compendium. For that purpose, space has been left in each year's entry after 1967.

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YEAR	EVENT
1888	First experimental demonstration of radio waves by Heinrich Hertz.
1890	Kennelly describes a low frequency experiment devised by Edison to correlate solar radio flux with coronal disturbances. Doomed to failure because of sensitivity and ionospheric cut-off. No record of the actual experiment.
1894 - 1900	Sir Oliver Lodge tries to detect centimeter wave radio radiation from the sun. Did not succeed due to interference and lack of receiver sensitivity.
1902	Kennelly and Heaviside discover the ionized reflecting layer in the terrestrial upper atmosphere that cuts off extra-terrestrial radiation below about 10 MHz.
1931 - 1932	Karl G. Jansky detects extragalactic emission at 20 Mc/s (14.6 meters). Attributes radiation to 1) a disk-like distribution of radio sources, 2) a different class of sources than the sun, since he didn't detect the sun, and 3) the cause was attributed to thermal agitation of charged particles with an effective temperature of about 15,000°K.
1933	Jansky notes coincidence of his main radio source component at $\alpha = 18^h$; $\delta = -10°$ with the galactic center.
1936	Arakawa in Japan finds a hissing noise accompanying sudden fadeouts at 4-20 Mc/s. The first evidence for the presence of solar non-thermal emission. H. W. Newton notes "radio fizzlies" on short wave communication links preceding fade-outs accompanying strong solar flares.
1938	D. W. Heightman observes a smooth, hissing sound at frequencies of 20 Mc/s and higher. More evidence for solar non-thermal emission.
1939-1940	Grote Reber maps the sky with 31 ft paraboloid at 160 Mc/s, finds lower intensities than Jansky, but has better resolution. Finds emission reaches a maxima near the galactic center in agreement with Jansky, but also finds subsidiary maxima, particularly in the direction of Cygnus. First possible observation of Cygnus A, but not so recognized at that time. Reber earlier tried observing at $\lambda = 9$ and 33 cm without success.

YEAR	EVENT
1940	Henyey and Keenan develop the theory of radio radiation from ionized gas in Ap. J.
1942	J. S. Hey in England detects the sun in conjunction with war effort. Used Army radar at 55-80 Mc/s, found emission to be correlated with the presence of a large sunspot on the disk of the sun. Simultaneously, G. C. Southworth at the Bell Telephone Labs in New Jersey detects the sun--the quiet component--at 10,000 Mc/s and at 3000 Mc/s a few weeks later. Their reports are classified and will not be made public until after the war.
1943	Reber independently detects the sun at Wheaton, Illinois, at 160 Mc/s. He publishes the first paper concerning the detection.
1944	H. C. van de Hulst in Leiden predicts the 1420 Mc/s line of neutral hydrogen.
1945	R. H. Dicke and R. Beringer detect the moon at 24,000 Mc/s. Dicke constructs a very sensitive switched microwave radiometer. Hey and collaborators detect and study meteors at radio wavelengths.
1946	Pawsey, Payne-Scott and McCready correlate solar radio noise with sunspot activity. Pawsey develops Lloyd's mirror interferometer. Circular polarization of solar radio emission (non-thermal) is detected. The first radar echoes are received from the moon. Work was done almost simultaneously by the Signal Corps Labs at 111 and 120 Mc/s and by Bay in Hungary at a higher frequency. The first application of interferometry in radio astronomy by Ryle and Vonberg, using a spacing of 140 λ at Cambridge. They find the angular size of the solar emitting regions to be less than 10 minutes of arc. Appleton and Hey point out the non-thermal character of solar emission. Hey, Parsons and Phillips find short period, irregular fluctuations at 64 Mc/s (5 m) from an intensity maximum in Cygnus. The angular size of the source is found to be less than two degrees. A. C. B. Lovell beings meteor research at Jodrell Bank. Covington begins solar observations at NRC, Canada.
1947	A 218-foot fixed antenna at Jodrell Bank is completed. Hey, Parsons and Stewart find transient echoes from meteors that originate from the E-layer of the ionosphere. They determine the first meteor velocities.

YEAR	EVENT
1947 (cont'd)	Payne-Scott, Yabsley and Bolton find solar outbursts to occur later at lower frequencies showing that corpuscular streams excite emission at the local plasma frequency as they travel outward through the solar atmosphere. Pawsey and D. F. Martyn discover the million degree solar corona. The first total solar eclipse is observed on May 20, 1947 by Hagen at 3.2 cm and by Khaikin and Chikhachev at 1.5 m. French radio astronomy group is founded at Meudon Observatory near Paris.
1948	Bolton and Stanley find that the angular diameter of Cygnus A is less than 8 minutes of arc, using the cliff-edge interferometer. Ryle and Smith discover Cassiopeia A. At the end of the year, ten radio sources are known.
1949	Piddington and Minnett study the variation in lunar thermal emission with phase of the moon at 1.25 cm. Cambridge and Jodrell Bank workers show the intensity variations of discrete radio sources at meter wavelengths to be ionospheric in origin. Bolton, Stanley and Slee discover Taurus A, Virgo A, Centaurus A, and Hercules A. They identify the first three sources with optical objects. By the end of the year radio observatories exist in England, Australia, Netherlands, France, Canada, the USA and the USSR.
1950	First external galaxy is detected by Hanbury Brown and Hazard (M 31). Ryle, Smith and Elsmore publish the first Cambridge catalogue of radio sources--50 sources. The 1C catalogue. The first parametric amplifier is built in the laboratory. Alfvén and Herlofson first suggest that synchrotron radiation may be of importance to the understanding of the non-thermal emission from many discrete sources. Stanier at Cambridge uses the first variable spacing, 2-element interferometer at 60 cm to derive the solar radio brightness distribution. Jodrell Bank 250 ft telescope project begins. Wild and McCready develop a radio spectrometer to measure, by sweep frequency techniques, the intensity of solar bursts as functions of both frequency and time. They describe Type I, II and III solar bursts. The 50-foot NRL parabola is completed, operating to $\lambda = 1$ cm.
1951	Little and Payne-Scott develop the swept-lobe interferometer at CSIRO to locate solar radio bursts.

YEAR	EVENT
1951 (cont'd)	Ewen and Purcell at Harvard discover the neutral hydrogen line predicted by van de Hulst. Confirmation comes within three months by observers at Leiden and Sydney. F. G. Smith determines the first precise (by optical standards) positions of bright sources. He finds that they have negligible parallaxes.
1952	Brown and Hazard detect Tycho's supernova 1572. Payne-Scott and Little show that Type II solar bursts travel outward through the solar atmosphere.
1953	Shklovskii suggests that the Crab Nebula is a synchrotron emitter. Mills constructs the Mills Cross (1500 ft arms, λ = 3.5 m). Jennison and das Gupta find Cygnus A to be a double source. Christiansen constructs the "Chris-Cross" grating interferometer at Fleurs (32 antennas in a cross operating at λ = 21 cm).
1954	The first MASER is constructed by Gordon, Zeiger and Townes. Kerr first detects 21 cm emission from an external galaxy--the Magellanic Clouds. Cyg A and Cas A are optically identified by Baade and Minkowski. Hagen and McClain first detect the 21 cm line in absorption towards Taurus A and the galactic center. Williams and Davies find line absorption toward Cyg A and Cas A. Baldwin and Dewhirst discover the SN remnant IC 443.
1955	Burke and Franklin at DTM discover non-thermal bursts of radiation at 22 Mc/s from the planet Jupiter. The first planetary detection. The second Cambridge catalogue (2C) is published, containing 1936 sources, many of which are spurious. The 85-foot dish at Leiden begins operation--the world's largest fully steerable telescope. The Caltech radio observatory is established with Bolton as first director. Baldwin and Mills suggest presence of a galactic halo.
1956	Mayer, McCullough and Sloanaker first detect thermal emission from Venus, Mars and Jupiter, using NRL equipment at high frequencies. NRL detects polarization in the Crab Nebula, finding 7% linear polarization at 3 cm. The 60-foot antenna at Harvard beings operation. Rishbeth at CSIRO observes the first lunar occultation (IC 443).

YEAR	EVENT
1956 (cont'd)	Heeschen first detects neutral hydrogen emission from a cluster of galaxies--the Coma Cluster.
1957	Browne, Evans, Hargreaves and Murray study radar scattering from the moon at Jodrell Bank. The 250-foot dish at Jodrell Bank begins operation. The spiral arms of the Milky Way are completely mapped for the first time by the Leiden and Sydney observers using the 21 cm line. The Mullard Radio Astronomy Observatory is established at Cambridge. Wild and Sheridan develop a swept frequency interferometer for solar applications. Boischot and Denisse recognize the association of Type IV solar bursts with solar cosmic rays.
1958	Drake and Ewen detect Saturn and a planetary nebula at 8000 Mc/s. The first radar echoes from Venus are obtained at Lincoln Labs. The first MASER is used in radio astronomy by Giordmaine, Alsop, Mayer, and Townes at NRL. Boischot establishes the characteristics of Type IV solar bursts, suggesting a synchrotron origin for the emission. Mayer et al. find 600 K temperature of Venus. The Cal Tech twin 90-foot antennas are completed. Sloanaker at NRL detects enhanced radiation from Jupiter at 10 cm. Coates at NRL makes the first observations at wavelengths less than 8 mm. The 85-foot NRL antenna is completed. The first Mills, Slee, Hill catalogue of southern hemisphere sources is published. Westerhout completes the first detailed study of HII regions at Dwingeloo.
1959	The first trans-Atlantic communication is made via the moon. Eshleman, et al. at Stanford first detect the sun by radar at 25.6 Mc/s. The Cambridge 3C catalogue is published, containing 471 sources. Suggestion is made by Drake and Hvatum that enhanced decimeter radiation from Jupiter is due to van Allen Belt around Jupiter.

YEAR	EVENT
1959 (cont'd)	A 22 m parabola operating down to 8 mm is completed at Serpukhov (USSR). Mills infers galactic spiral arm structure from continuum studies of non-thermal radiation. The 85 ft Michigan and NRAO 85/1 Tatel antennas begin operation.
1960	Morris and Berge observe Jupiter's van Allen Belts at 31 cm at Cal Tech. Palmer and Jodrell Bank workers achieve 2" of arc angular resolution of discrete radio sources using interferometry. A detailed investigation at 21 cm of the galactic center region is completed by Oort and Rougoor at Leiden. They find the 3 kpc expanding arm. Sandage finds the optical counterpart of the source 3C 48 to be a 16th magnitude point object after an accurate position determination by Matthews. Minkowski optically identifies 3C 295 with a galaxy having a redshift of 0.46 the velocity of light. Ryle and Hewish first describe the technique of aperture synthesis. Pettengill develops the technique of range and Doppler radar mapping. The new system of galactic coordinates is adopted. F. D. Drake observes Epsilon Eridani and Tau Ceti at 21 cm, searching at NRAO for intelligent signals from planets surrounding nearby stars (Project Ozma).
1961	General polarization of galactic background is found by Leiden and Cambridge groups. Hogbom and Shakeshaft find Cas A flux density to decrease at rate of about one percent per year in agreement with Shklovskii's 1960 prediction. Howard, Barrett and Haddock detect and measure radio emission from Mercury at 3-4 cm wavelength and infer a warm sub-surface temperature on the dark side. The Parkes 210-foot dish is completed. The first flare star observations are made by Lovell at Jodrell Bank and by Slee at CSIRO. Five "quasi-stellar" radio sources are now known. The first large scale study of brightness distributions is made at Cal Tech by Maltby and Moffet. Hey completes a two element 25 m variable spacing interferometer at Malvern. Radar observations of Venus establish a precise value for the astronomical unit. The Millstone Hill 84 ft goes into operation.

YEAR	EVENT
1962	First Mercury radar contact is made by Kotelnikov in the USSR at 700 Mc/s. The 300-foot antenna at Green Bank is placed in operation at $\lambda \geq 20$ cm. Kraus completes construction of Ohio State 2 reflector antenna. Morris and Berge infer that the magnetic axis of Jupiter lies at a 9° angle from the axis of rotation since they found a periodic rocking in the direction of polarization of the radio radiation from Jupiter. Three occultations of 3C 273 allow Hazard, Mackey and Shimmins to determine an accurate position of the source.
1963	The 1000-foot fixed dish in Arecibo is completed. Barrett, Meeks, Weinreb and Henry discover the OH line at 1665-1667 Mc/s (MIT, Lincoln Labs). Confirmed by groups in CSIRO, Berkeley and Harvard. Zeeman splitting of the HI line is detected, showing the presence of a galactic magnetic field with strength about 25 microgauss. Mars is first detected by radar at JPL at 2388 Mc/s. Schmidt finds the quasi-stellar sources to be objects with very large redshifts. Ryle's One-Mile radio telescope interferometer is completed at Cambridge (3 elements, 60 ft diameter operating at 408 and 1407 MHz). The Aerospace 16 ft millimeter wave antenna begins operation. The University of Texas 16 ft millimeter wave antenna begins operation. Conway, Kellermann and Long publish definitive data on 160 radio source spectra, extending these spectra to centimeter wavelengths. Gardner and Whiteoak at CSIRO use polarization measurements of discrete sources to determine the direction of the magnetic field at the source through extrapolation techniques. Hazard finds 3C 273 to be double with component B coinciding with a 13th magnitude blue star. Schmidt finds a jet coinciding with component A and determines a redshift of 0.158. H. Smith and Hoffleit find variability over an 80 year interval. Greenstein and Matthews find a redshift of 0.367 for 3C 48.
1964	The Mark II 120 x 80 ft elliptical antenna is completed at Jodrell Bank. The 120 ft Haystack antenna is completed at Lincoln Laboratory, MIT and is capable of 1 cm operation.

YEAR	EVENT
1964 (cont'd)	Bigg finds that the probability of occurrence of Jupiter bursts is strongly related to Io, the closest Jovian satellite. Carpenter and Goldstein at JPL establish a 250 day retrograde rotation period of Venus. The NRAO interferometer begins operation with the addition of the 85/2 antenna. The French 2 reflector antenna at Nançay begins operation. Matthews, Morgan and Schmidt first distinguish the types of optical galaxies that are associated with strong radio sources. Rapid radio source scintillations are found by Clarke and are later shown by Hewish, Scott and Wills to be caused by irregular ionization of the solar wind in front of sources having angular diameters less than about 1" arc.
1965	The NRAO 140 ft telescope is completed and begins operation with the confirmation of the Russian discovery of a hydrogen recombination line by Mezger and Höglund. Pettengill and Dyce deduce a rotation period of 59 days for Mercury based on Arecibo radar data at 430 MHz. OH in emission is detected by Weaver's group at Berkeley. Originally termed "mysterium", the strong, narrow lines indicate a maser origin for the emission. Penzias and Wilson discover the isotropic 3°K background radiation from the universe---presumably relict radiation from the "big-bang" fireball from which the universe evolved. Dent discovers the first clear evidence of radio variability in an extragalactic source when he shows that 3C 273 has increased 40% in flux density at 3.75 cm in three years. F. G. Smith and J. V. Jelley detect bursts of radio emission by Cerenkov radiation resulting from cosmic ray showers entering the earth's atmosphere.
1966	The Canadian 150 ft telescope is completed at Algonquin Park. Uranus and Neptune are detected at radio wavelengths. The helium recombination lines are detected by Lilley, et al. The 22 m millimeter wave antenna at Crimea, USSR begins operation.
1967	First Very Long Baseline interferometer observations are conducted by the Canadians with resolution well below one arc second now possible. Molonglo Cross is completed by Mills (mile long cylindrical parabolas, operating at 408 and 111.5 MHz).

YEAR	EVENT
1967 (cont'd)	Wild completes the Calgoora solar radio heliograph which produces rapid pictures of solar radio activity at 80 MHz using a 96 element system of 13 m steerable parabolas in a 3 km diameter circle. Hewish and Dennison deduce from source scintillation measurements the speed of the solar wind (~300 km/sec) and the size scale of the irregularities (~200 km). Cohen and Gunderman show that 3C 279 has a component less than 0".005 arc (13 pc) from scintillation data. Bell and Hewish at Cambridge discover the first four pulsars but do not report them for 7-8 months while the nature of the sources is being established. The Jodrell Bank Mark III antenna is completed. Aller and Haddock find changes in the radio polarization of selected quasars.
1968	The NRAO 36-ft millimeter wave telescope begins operation on Kitt Peak. T. Gold suggests that pulsars are rapidly spinning neutron stars. Staelin and Reifenstein find the pulsar in the Crab Nebula using the NRAO 300 ft. It is the fastest (33 ms) and probably youngest pulsar known. Townes and the Berkeley observers detect lines of NH_3 and H_2O near 1 cm in interstellar clouds. Cal Tech 130 ft antenna begins operation. The 85/3 antenna is added to the NRAO interferometer. Wilson and Barrett discover OH emission from infrared (IR) stars. The first estimates of pulsar distances are made from neutral hydrogen absorption studies in directions toward pulsars.
1969	Cocke, Disney and Taylor find the optical counterpart of the Crab Nebula pulsar, coinciding with the star Baade identified as the exploded supernova. Formaldehyde (H_2CO) is detected on the 140 ft telescope at NRAO by Buhl, Snyder, Palmer and Zuckerman.

YEAR	EVENT
1969 (cont'd)	Cal Tech and NRAO observers test the General Theory of Relativity by noting the gravitational deflection of 3C 279 as it is occulted by the Sun. The first US-USSR joint VLB interferometer experiments are run.
1970	The Westerbork interferometer comes into operation (12, 25 m reflectors on an E-W line 1.6 km long, with 2 end dishes movable on rails). CO, CN, HCN, H_3CN, CH_3OH and "X-ogen" are detected by various groups, using the NRAO 36 and 140 ft telescopes. The Stanford 5-element array begins operation at 10.7 GHz. The Illinois 120 ft paraboloid is completed. The four 120 ft spherical reflectors go into operation at the Five College Radio Observatory. The Kharkov T-dipole array begins operation at 26 MHz. Gottesman and Gordon detect radio recombination lines from the diffuse interstellar gas at 18 cm.
1971	The 250 ft Mark I Jodrell Bank antenna is modified to upgrade surface and steering accuracy. CS, NH_2COH, OCS, SiO, CH_3CN, HNCO, HNC, CH_3CCH and CH_3CHO are detected by various groups, using the NRAO 36 and 140 ft telescopes. The Ooty occultation telescope begins operation at 327 MHz. Wade and Hjellming detect radio emission from the B3 companion of the M supergiant star Antares, Algol and β Lyrae and find variable radio sources associated with X-ray sources Scorpius X-1, Cygnus X-1 and GX 17+2. Weliachew detects OH absorption in the galaxies NGC 233 and M 82. VLB observers at 6 cm are resolving source structure down to resolutions of 0.4 milliarcseconds over baselines of 10.536 km.

YEAR	EVENT
1972	Completion of Cambridge 8 element, 42 ft, 3 cm, 5 km interferometer. The Bonn 100 m steerable paraboloid begins operation. Penzias, Jefferts and Solomon discover deuterium as a component of the DCN molecule, using the NRAO 36 ft. telescope. Radio bursts are detected from Cygnus X-3 by Gregory and observatories throughout the world monitor the burst activity. The Very Large Array (VLA) receives its initial $3M funding for the construction of a 27 antenna array on the Plains of St. Augustine, 50 miles west of Socorro, N. M.
1973	Turner and Meudon observers simultaneously discover OH absorption in Comet Kohoutek. Continuum emission at 1 mm is found by a French team using the NRAO 36 ft telescope. This is the first confirmed comet detection at radio wavelengths. Brown and Roberts discover a narrow radio absorption line in 3C 286, presumably a redshifted 21 cm line at z = 0.692. The first asteroid, Ceres, is detected by F. H. Briggs, using the NRAO interferometer at 3.7 cm. De Young, Roberts and Saslaw detect several narrow absorption features at the 21 cm line in Perseus A (NGC 1275). The velocities cluster at a velocity about 3000 km/sec greater than the systemic velocity of the peculiar galaxy.