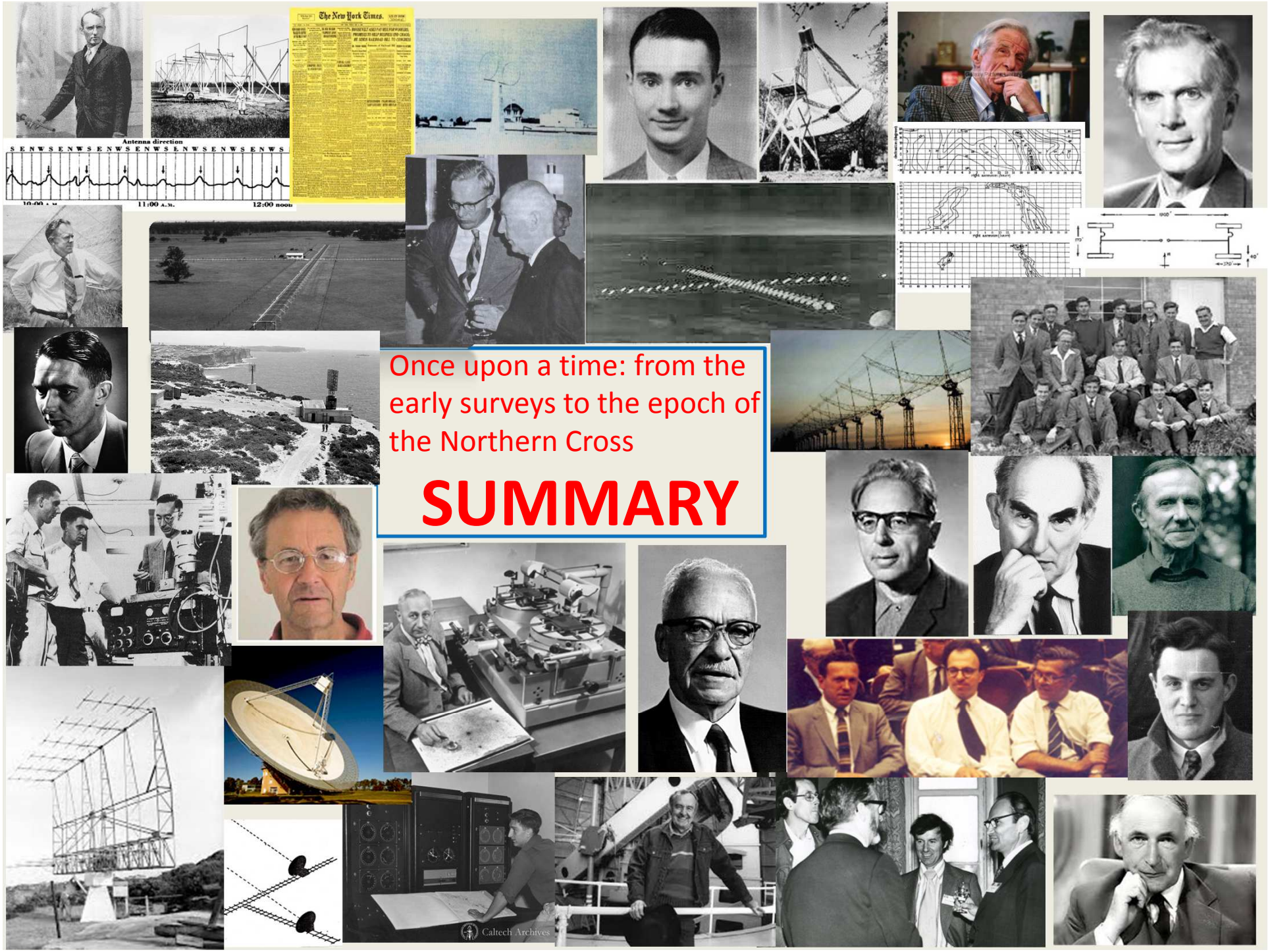


Once upon a time: from the early surveys to the epoch of the Northern Cross

SUMMARY

20 years of surveys (discoveries, consciousness & impact)
From *radio M.W* to *extragalactic radio sources*

1) The origin of the M.W. radio emission: *cannot be only thermal !!*

and discrete sources: *are they stars?*

(the two problems remained tangled for years)

2) First visual counterparts: *galactic* or *extragalactic bodies?*

3) Go to **1)**: *individually unresolved radio stars?* OR

Synchrotron radiation in the diffuse medium?

4) Reliable optical identifications: *galactic & extragalactic nebulae;*

never stars

5) Entry into *cosmology* & into *physics*

6) Radio astronomy has come of age (about 1960) :

many big radio telescopes and surveys: birth of the Northern Cross

Once upon a time .... (1932-1945 circa, *meter* λ)

✓ Karl Jansky (1932) detects **radio signals** from Sagittarius direction

✓ Grote Reber (1937 & followings) maps radio emission from the **whole M.W**

WHAT can produce radio emission from the M.W. ??

➢ Thermal free-free transitions (Henyay & Keenan, 1940) (bremsstrahlung) ??

no detection at short λ; T_b too high ($\approx 10^5$ K) at decametric λ (Townes, 1947)

✓ Hey (1942) *serendipitously* discovers that **SUN** emits radio waves, *variable in time*

(two german warships travelled the Channel undiscovered because the (then active) Sun had blinded all radars)

➢ Could ***all sun-like stars,*** individually *unresolved*, **produce** M.W. radio emission??

NO: they would produce an emission 10^{-12} $10^{-9}$the observed one (Greenstein al., 46)

➢ Moxon (1946) M.W. spectrum (40, 90, 200 Mc/s), S$\propto \lambda^{0.7}$, is **non-thermal:**

is there something different in addition to free-free ?

A One-source survey (after the war)

- Hey, Phillips & Parsons (1946) come across a region (**size < 2°**)

  in **Cygnus constellation**

  showing 15% variability (few seconds - few min, similar to Sun);
- Bolton & Stanley (1948) confirm Cyg variability and give **size < 8';**

  $T_b > 4\ 10^6$ K: *too high*

Cyg must be a ***discrete source*** (later on named Cyg A)

Impact: discrete sources *exist*

distinct from M.W. diffuse emission

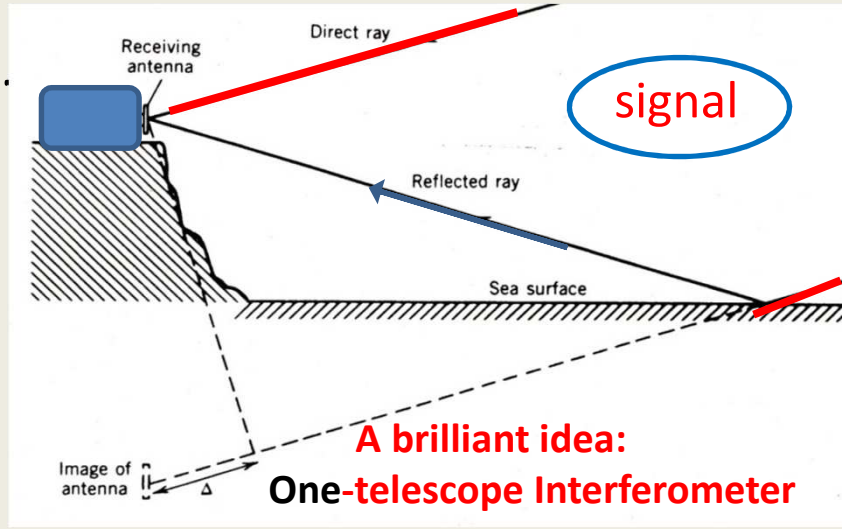
emission mechanism as in the Sun?

a-few source surveys (1948)

- Bolton 1948 (Sydney) Sea cliff Interferometer, 100 (60, 85, 200) Mc/s

✓ **6 more *discrete* sources: *in*** Taurus ,
Coma Berenices, Hercules, Centaurus + 2 r.s.

are they **anomalous stars** (out of main sequence) contributing to M.W. emission, *in addition* to free-free ?



- Ryle & Smith 1948 (Cambridge)
Michelson-type interferometer, 80 Mc/s,

✓ **Cyg A** (shortest *burst duration* ≈ ***20 sec***) size similar to Sun size **a** (radio) **star?!**
(believed intrinsic) T_b>10^{14} K (too high to be thermal)

✓ discovery of Cass A, Ursa Major (+ few more r.s.)

✓ search for Circular Polararization (present in Sun) in Cyg A: **not found**

NO circular polarization in Cass A and Cyg A

→ **NO Sun-type**

First *tentative* Optical Identifications (ID)

- *«accurate* (5'-10 ')» *positions* for Taurus, Virgo, Centaurus (New Zealand)
  & tentative optical ID from catalogues (Bolton, Stanley & Slee, 1949)
  - ✓ Taurus A (Crab nebula), SNR:
  - ✓ Virgo A & Centaurus A, nebulae (M87 & NGC5128)
    generally classed as extragalactic (e.g. Shapley & Ames, 1932).

Bolton et al., 1949: *«Neither of these objects has been resolved into stars, so* ***there is little definitive evidence*** *to decide whether they are true* ***extragalactic*** *nebulae or diffuse nebulosities within our galaxy»*

(Hubble & Humason 1931 classified M87 as E0 in Virgo cluster and measured a recession velocity of 800 km/sec)

of the *dozen* discovered «radio stars», only for three an optical ID is suggested, but

Not with stars ……

② scenarios for *non-thermal* radio emission of M.W.

1) Individually unresolved Stars

➢ Ryle (1949, 1950): **very hot stars,** like Cyg A ($T \approx 10^{14}$K).

«Strongly Magnetized fast rotating stars » (Alfvén 1937)

✓ similar models: Unsöld, 1949 and Alfvén & Herlofson, 1950

❖ Westerhout & Oort (1951), Bolton & Westfold (1951), H.Brown & Hazard (1953) model *expected **spatial** distribution* of M.W. radio radiation .

All three papers suggest an **extragalactic *contribution***

❑ optical ID by Baade & Minkowsky *(see later) weaken* radio star hypothesis (1953)

❑ discrete source counts *change* most radio stars *into* extragalactic radio sources (1955)

② scenarios for *non-thermal* radio emission of M.W.

2) **Magnetic Bremsstrahlung** (named «Synchotron» by Oort Walraven, 1957)

- Kiepenheuer (1950): radiation is produced in **interstellar space** by relativistic $\boldsymbol{e^-}$ (in cosmic rays) in $\boldsymbol{H_{gal}}$, just discovered (≈ 1% of cosmic ray $e^-$of 10^8eV + $H_{gal} \approx 10^{-6}$ G reproduce M.W. luminosity at 100 MHz).

  Ignored (?) in western countries

- In *USSR* Synchrotron theory is taken very seriously (e.g.Ginzburg 1953, Shklovsky 1953). For them **«radio stars» are *dead & buried*…..**

- They develop the theory and ***stress*** that radiation is **polarized**

- They propose Synchroton **also for discrete sources**

half of fifties and more

➢ discrete sources:

- ✓ Oort & Walraven (1956) in Crab, Baade (1956) in M87 find *optical polarization* supporting Synchrotron theory
- ✓ Burbidge (1959) applies to extragalactic radio sources Synchrotron theory and shows how to evaluate energies of *H* and relativistic particles

➢ M.W. diffuse emission is *now* disentagled from discrete radio sources

- ✓ Mills (1959) decompose the radio spectrum of M.W. (3.5m + 22 cm by Westerhout 1958) *assuming* that **non-thermal fraction** of radiation is by **synchrotron**
- ✓ Westerhout (1962) detects M.W. polarization (first positive attempts: Razin 1958-2-4% at 207 MHz, Thomson 1957, 1% at 160 MHz)
- ✓ cosmic ray electrons discovery (Earl 1961 , Meyer & Vogt 1961)

few-ten source surveys (1950-1955)

Authors	# r.s.	freq. MHz	S_{min} (Jy)	Pos.acc. Pri. beam	Sky region	Instrument
Stanley & Slee (1950)	22	100	100	9^ox17^o	$-50^o<\delta<+50^o$	Sea Interferometer
Ryle,Smith & Elsmore(1950)	50	81	30	≈1'x5' 1.5^ox90^o	$+12^o<\delta<+82^o$	Phase switch interferometer
Mills (1952)	77	101	50	2min (RA) 14^ox24^o	$-90^o<\delta<+50^o$	Michelson-type Interferometer 2 EW baselines
H. Brown & Hazard (1953)	23	158	5	3m x 2^o 2^ox 2^o	$+38^o<\delta<+68^o$	JB 218ft transit Paraboloid
Shain & Higgins (1954)	37	18.3	2500	1^ox5^o 17^ox17^o	$-52^o<\delta<-12^o$	Sydney, 30 λ/2 Dipole Array
Bolton, Stanley & Slee (1954)	104	100	50	Fringe spacing 1^o	$-50^o<\delta<+50^o$	Sea Interferometer

≈ 150 different r.s, meter λ, S > 10 Jy, degrees resolution

Impact on the nature of «radio stars»

- Bimodal distribution of radio sources in the Galaxy: (Mills 1952, ….)
  - ✓ Concentration about Galactic Plane ($|b|<12^o$) of the strong (S≥300 Jy) r.s.
    Class I = galactic (not found by Ryle et al.; resolved by interferometer??)
  - ✓ Uniform distribution in $|b|$ of the weak ones
    Class II = weak close and galactic, **OR** strong and extragalactic
- Source counts: $N(>S) \propto S^{-\delta}$ (*ogive*):
  - ✓ **Class I** δ=0.75: consistent with a random *disk distribution* (same as mag<15 stars
    galactic nature confirmed
  - ✓ **Class II** δ=1.5*: homogeneous distribution*: extragalactic **OR**
    feeble & at a short distance - *within the disk*

*«it does not seem possible to suppose that the **majority** of the observed **radio stars** are outside our galaxy because of **theoretical difficulties encountered** in attempting to explain the very great **intensities** of the more intense radio stars»* (Ryle, Smith, Elsmore 1950)

- Cass A diameter: *a few arcmin* (H.Brown & Hazard 1953).
  «If this source is typical of Class I, this Class cannot be identified with bodies of stellar dimensions»
- Few determined radio spectra are *non-thermal*

unambiguous optical ID (Baade & Minkowsky 1953 JB Symp., 1954)

48 / 200 inch tel. pointed at best available positions. Some notable cases:

- *galactic nebulae :* **Cass A** (optical diameter≈5-6 arcmin, like in radio) & **Puppis A**
- *extragalactic nebulae:* **Cyg A** – 2 galaxies in collision **z=0.056** (pretty high for that epoch); (earlier suggested by Mills 1951); **NGC 1275** (in Perseus; galaxy collision?); **Cen A** (dark band- ***E*** & ***S*** galaxies in collision?); **M 87** (M 87 & Cen A see initial ID by Bolton '49)
- **Several spirals** *(considered like M.W.)*

***Cyg A no more a radio star**: radio star hypothesis begins to creak….*

Cyg A could have been detected also at much larger distance, out of reach of 200 inch

does radio see farther than optical?

- *«**Under the impression that all sources identified so far are extended or of extragalactic origin,** **the concept of stars as radio sources has dropped into the background**. It seems necessary to emphasize that an interpretation of the distribution of the general galactic radiation meets great difficulties **without the assumption that radio stars exist»*** (Baade & Minkowsky 1954)
- «Ryle (Jodrell Sym. 1953) *«It appears that we have both galactic and extragalactic sources and the question arises as to whether the **galactic sources** can account for **the radiation from the Galaxy**»*

a-few-thousand source surveys (1955-1960)

radio astronomy joins cosmology

- Shakeshaft et al (1955): 4-element interferometer, ν=80 MHz; primary beam 1^ox7.5^o, positional accuracy 2'x12' for strong sources; S_{lim} few Jy; $-38^o<\delta<83^o$; 1936 r.s.; **2C** survey
- Mills & Slee (1957): Mills cross (450 m x 450 m); ν=85 MHz; HPBW=50'; S_{lim} ≈ 8 Jy 0-8h , $-0^o<\delta<+10^o$; 383 r.s.; **MS** survey
- Mills, Slee & Hill (1958-61); completion (24 h) of *MS*

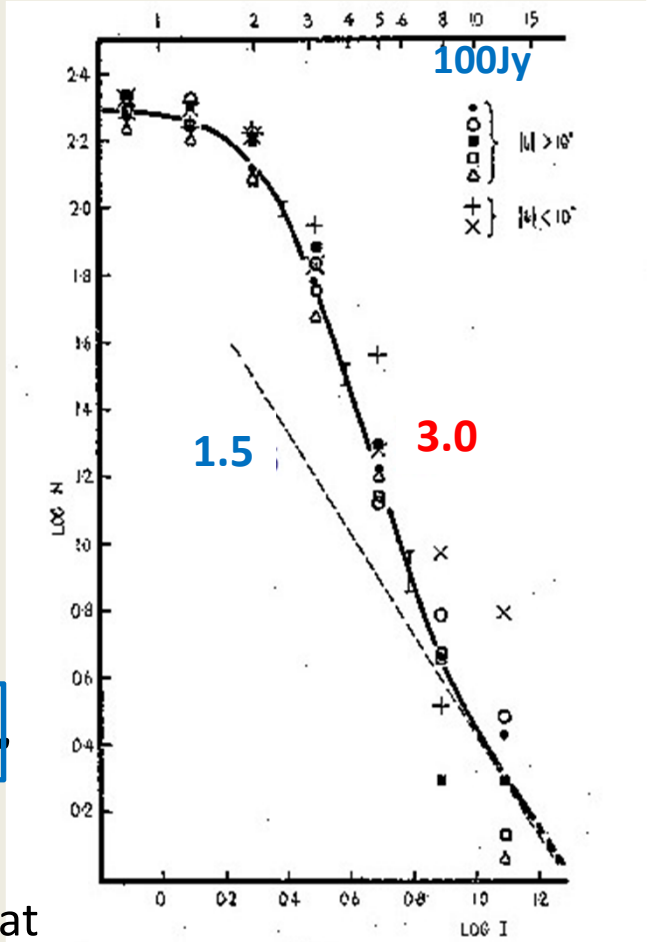
1700 r.s.; ***MSH*** *survey*

2C Source counts (N$\propto s^{-\delta}$)

Log *N* / Log *S* (Ryle 1955): **$\delta \approx 3$**

too steep for a galactic distribution.

«Hard to avoid the conclusion that most radio stars are extragalactic».



Moreover data contradict Steady State Theory (SST) which requires **$\delta \leq 1.5$** (Bondi & Gold, 1948; Hoyle, 1948):

The Universe appears ***to be evolving….***

Scheuer 1990, «Modern Cosmology in retrospect» says that

«Ryle's attitude on radio stars changed almost overnight – winter 1954»

….. embarassing ….

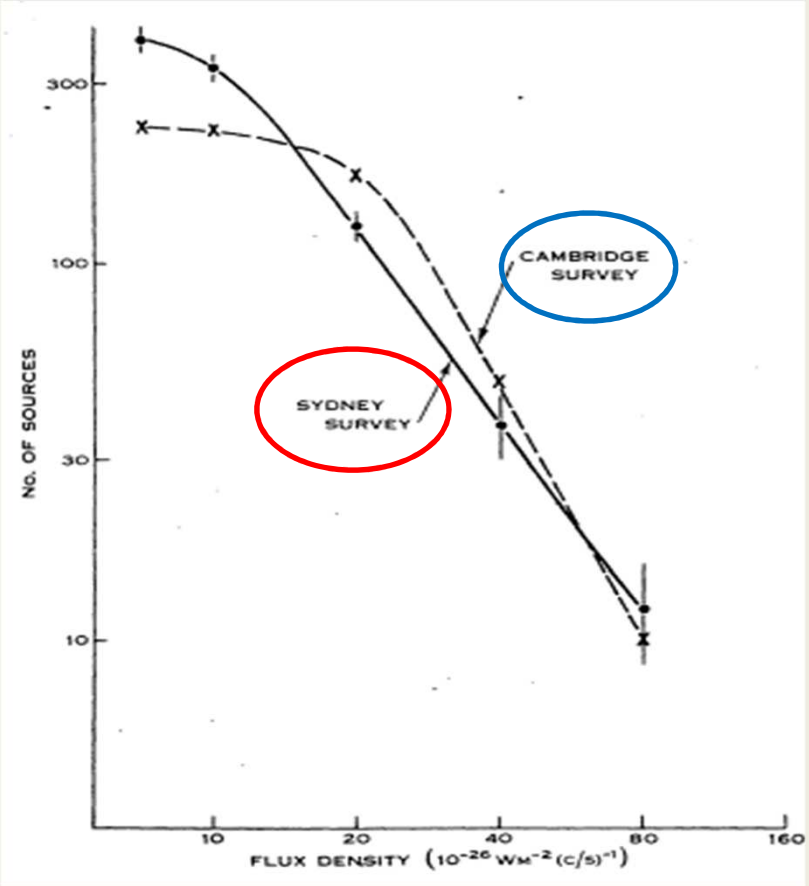
Ryle presents his results at the Halley Lecture (Oxford, May 6, 1955):
first strife with Gold

Pawsey presents preliminary Log N / Log S from *MS survey* at
IAU Symposium on Radio Astronomy (Jodrell Bank 1955)
slope (for class II) is **1.65** *compatible* with δ**=1.5**.
Gold takes the chance to criticize Ryle

Bolton (1955), soon after the Jodrel Symp., in a letter to «Observatory»
suggests that the *strong steepening* of
2C Log N / Log S is *due to confusion effects*

(Ryle et al. were conscious of confusion problems, but they thought, on the contrary, that the effect of confusion be to make faint sources disappear)

MS *vs* 2C source counts (Mills 1957)



«the two catalogues are almost completely discordant».

too many 2C sources not found in *MS*
(even allowing for some lobeshift in 2C)

Paris IAU Symp (1958) a heated **discussion on SST continues** not only between Ryle and Mills but ***also with cosmologists*** (Hoyle, McVittie) who object that source counts *«may not be adequate to select a unique cosmological model»*

(but this is not the point)

The debate on source counts continues

Edge, Shakeshaft & McAdam (1959), very quickly move

2C interferometer frequency to ν=159 MHz; (4 times smaller beam)

less confusion…..; S_{lim} ≈ 10 Jy ; -22°<δ<+71° **471 r.s.; 3C** survey

3 out of 4 2C sources are not confirmed!

New slope is δ**=2.2** still higher than Mills'.

After three years of refinements, confusion corrections (Scheuer method, 1957),

re-observations with the new *Aperture Synthesis Radio Telescope*

the *first* revision of the 3C survey **(3CR)** is ready (Bennett 1962): a «complete»

sample of **328** strong (>9 Jy) r.s. at 178 MHz, dec. > -5° (*final rev.* **3CRR**, Laing et al. 1983)

Finally δ slowly has converged to **1.8 ± 0.12,** close to Mills'

(Scott & Ryle ,1961; Bennett, 1962….. ……Gower, 1966 – **4C**)

……BUT ……..

The two groups **still disagree** about the **compatibility** (Mills) with Steady StateTheory **or not** (Ryle)

Scheuer (1990, «Modern Cosmology in Retrospect»), referring to his visit at CSIRO (1959-1962 circa), says:

«… *I got to know him (Mills) a little and we got along pretty well,* ***though we never did agree about radio sources*****»**

In 1965 the discovery of the *Microwave Background Radiation*

closes the debate (not for everybody, however….).

Multi-ν & High resolution: (> 1960)

- **radio spectra** from 10s MHz to a few GHz ($S \propto \nu^{-\alpha}, \alpha \approx 0.7$)
- **morphology** at high resolution (two-sided)
- **accurate positions + PSS** *boom* of optical ID: R.G + Quasar discovery ≈1961 (are radio stars resurrected?)

***Impact* on physics *of radio sources* and cosmology**

- Radio Galaxies: *standard candles* for cosmological tests (Sandage 1964-72)

…… the epoch of the Northern Cross (1960 circa)

Most problems (extragalactic nature, synchrotron, ….) solved

flowering of radio telescopes and surveys

- aperture Synthesis (Cambridge): 4C interferometer (1.2 km EW x 1 km NS)
  One-Mile interferometer ***(Earth Rotation)*** *(Ryle, Nobel Prize 1974)*
- large dishes: Jodrell Bank Mk I, (250-ft); Parkes, (210-ft); Green Bank, (300-ft, 140-ft)
- Cross Radio Telescopes:

✓ Benelux (Belgium, Netherlands, Luxemburg), 5 km x 5 km, (Oort idea….) transformed into WSRT;

✓ DKR-1000 (Pushchino, km x 1 km); **multi-λ (2.5-10m);**

✓ Molonglo Cross: (1.6 km x 1.6 km), Northern Cross (600 m x 600 m)

- **4C:** 178 MHz, $20^o < \delta < 40^o$; **4843 r.s.** S > 2Jy
- **PKS:** 408 MHz (+ 1410 & 2650), $-90^o < \delta < +20^o$; **1780 r.s.** S > 4 Jy;
- **NRAO:** 5GHz, $0^o < \delta < 70^o$; **550 r.s.** S>0.6 Jy (0.8) (+ deeper survey & other ν)
- **MC1,2,3:** 408 MHz, various regions; **2811 r.s.** S > 0.1 Jy (to be continued)
- **5C1,2:** 408 (& 1407) MHz, various regions, **313 r.s.,** S > 10-20 mJy (to be continued)
- **B2 & B3:** 408 MHz, ≈ **24 000 r.s.** *(see more)*

The Northern Cross

original project 1.2 km x 1.2 km

Marcello, why don't you build a radio telescope?

Main Purpose: to carry out **a large ($> 10^4$ sources) deep (tenths of Jy) survey** in order to build an accurate confusion-free Log N / Log S

(to set a final word on the SST debate)

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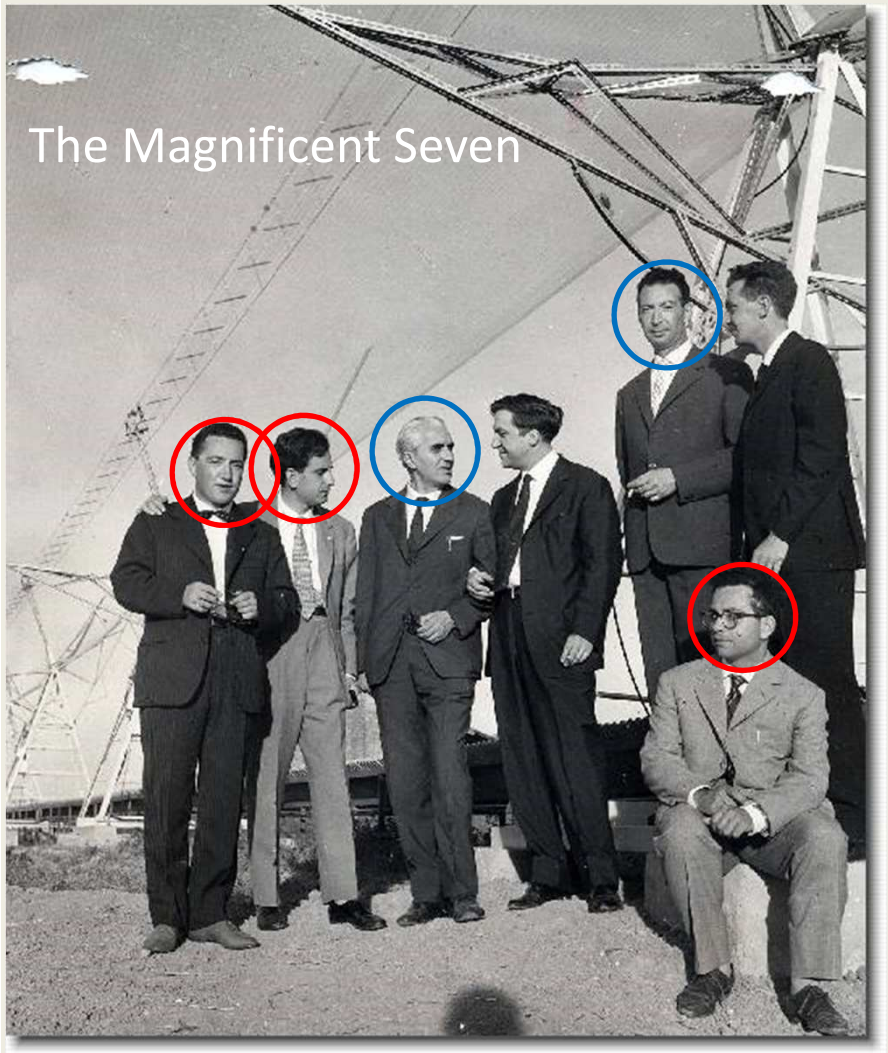

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the EW arm first frame (1963 circa)

the EW arm is ready (408 MHz)

1964 – EW arm (564m x 35 m) (+ 320m x 47m only of NS arm because of delays in fundings). EW arm divided into 6 sections to have

3 EW independent beams (HPBW 4' x 110') *(opening Oct, 24)*

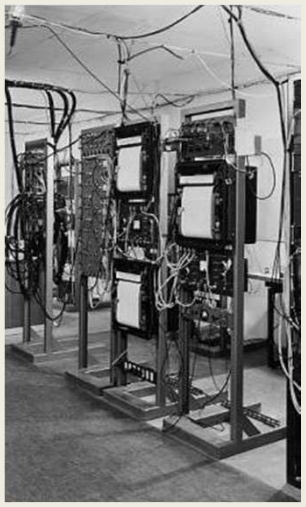
The B1 Survey (EW arm only)

Dec. 15, 1964-Jan. 2,1965 ; noise ≈ 0.06 Jy

0h< α <13h (free of man-made interferences)

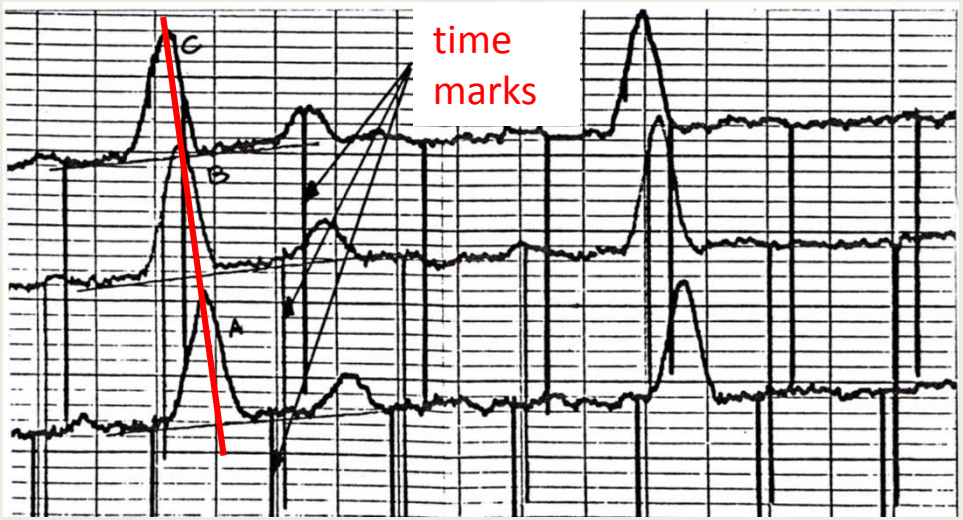
-30°< δ< -20° (overlap Parkes), S > 1 Jy

624 r.s. in 0.6 ster.



≈2 Jy sources →

← *chart recorders*



On Novembter, 5, 1965 the **Italian Physical Society** *awards a prize of* ***500 000 lire*** *(equivalent to today 4000 US$) to the* **Northern Cross**

Ceccarelli & Mannino (full professors) let the prize be divided among the **24 members of the group (technicians, secretary, researchers)**

I had the honor to collect it, on behalf of the group, in the *Stabat Mater Hall in Archiginnasio,* first seat of the ancient Bologna University*)*

The 600m x 300m Cross (B2 Survey)

- End ’66: no further money. Work starts to make NS arm operative
- Christmas 1967: 3 NS beams; 3 x 3 pencil beams (3’ x 10’)
  on the sky (5 x 3 beams after1970).

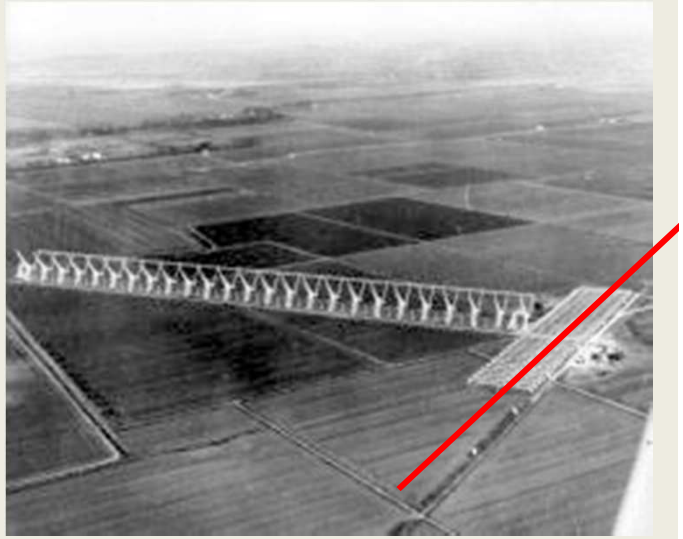
- Test Mini-survey **(GV)**: $34^o < \delta < 35^o$, $07h40m < \alpha < 18h20m$
  (covered by Schmidt 48 inch multicolor plates); **328 r.s.** S>0.15 Jy, 0.04 ster
  (no confusion above ≈0.25 Jy)

- Autumn ’68-End ‘72: B2 survey (4 sections):
  $21^o40' < \delta < 40^o18'$ ≈10000 r.s, S_{min}=0.2 Jy
- Data analysis almost completely computerized !!!

Cross ***final*** configuration: **a *Synthesis Telescope***

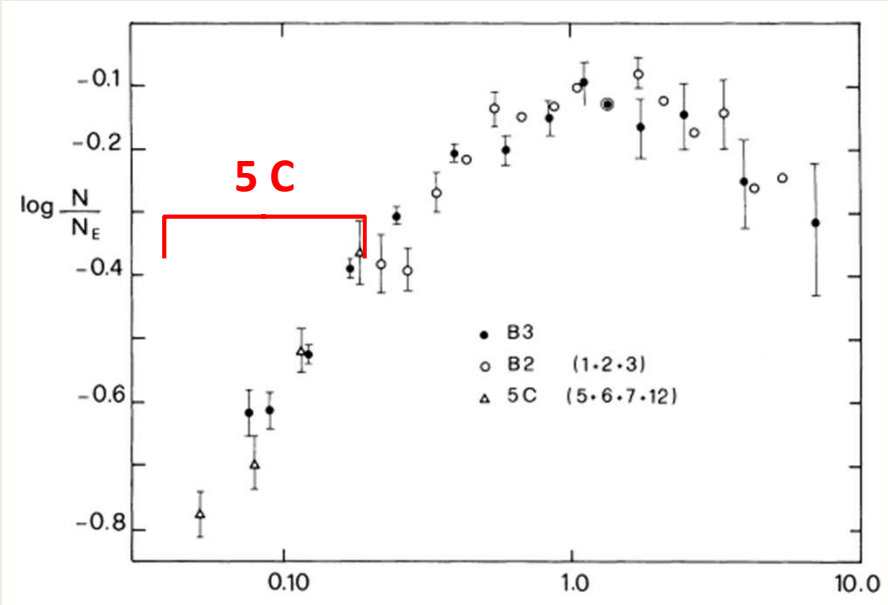
1972-76: entire electronic improved; NS arm extended to 600 m *(financed by CNR)*

(beam 2.6’ x 4.8’at zenith)



The 320m NS arm is cut and redistributed in length producing an array twice as long and a half as large

Differential normalized Log N / Log S



8 NS arm sections:

6 x 8 complex correlations

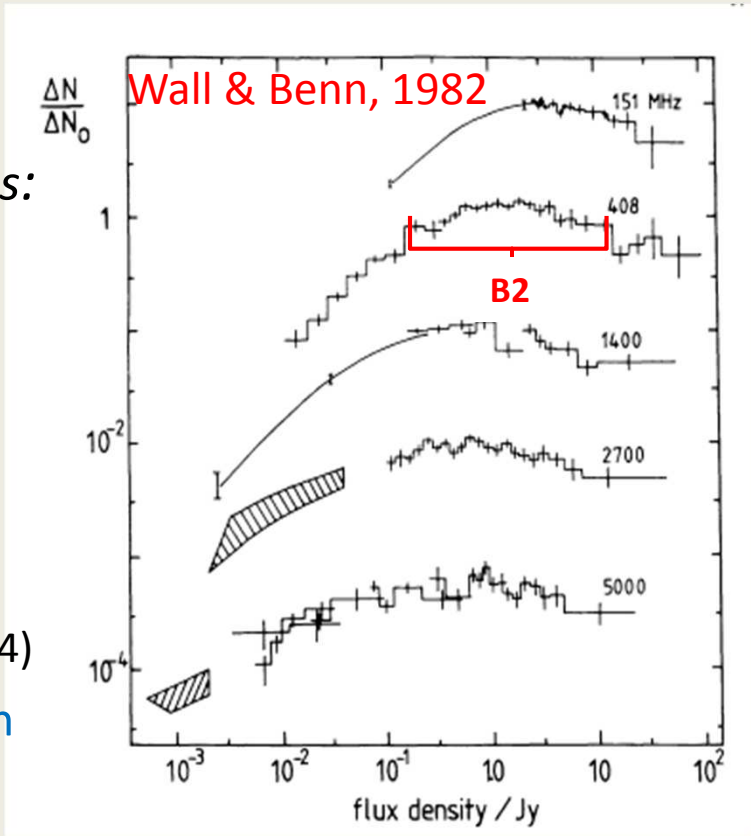
0.5^{o} synthesis strip/scan

B3 survey **13354 r.s.**

S>0.1 Jy 35^{o}45’ < δ< 49^{o}15’

The Northern Cross provided the scientific community with a large set of data, useful to study, at a frequency different from that of the **3CR** and at much lower flux densities, extended samples of extragalactic radio sources.

Bologna surveys allowed to bridge the gap in luminosity between high power **3CR** and 10-**mJy surveys** (**5C** at the epoch). *Two examples:*



- ✓ Investigate the **Log N / Log S** at various ν:
  B2 r.s. are located where the maximum deviation from uniform distribution occurs

- ✓ **1Jy sample** (selected from B2, Allington-Smith,1984) to study the processes of formation and evolution of radio galaxies up to ***z=3***

in addition

The onset of a solid research group led to the creation in 1970 of the ***Istituto di Radioastronomia*** (IRA) of the National Research Council **(CNR),** with a permanent scientific and technical staff, and regular fundings

CNR financed also the construction of the two 32m VLBI parabolae (Medicina & Noto) and supported for years the VLBI operations in Italy.
It has also promoted the 64m SRT project. All three antennas were designed and managed by IRA

Members of IRA (now IRA-INAF), in addition to VLBI, have been involved in several international projects such as ALMA, LOFAR, and those being discussed in the present meeting.

Thank You for Your Attention!