Notes for Summer Student Lecture 1973

EXTRAGALACTIC RADIO ASTRONOMY

E. B. Fomalont

I. INTRODUCTION

A. In these notes an overview of problems and data in extragalactic radio astronomy. More details in other lectures.

Ref: Synch. Radiation - Peterson
Long Baseline Interferometry - Kellermann
Cosmology - von Hoerner
Interferometry and Aperture Synthesis - Balick
Structures - Palmer
Linear Polarization - Bignell
Spectra - Condon

B. Outline of Notes.

1) The radio astronomy universe and where to find it.
2) Observational instruments and description of the relevant data.
3) Interpretation (i.e. wild guesses) of radio data.

II. RADIO UNIVERSE AND WHERE TO FIND IT

A. Picture of the Radio Sky.

Milky Way and isotropic component

Early identifications - sources fairly distant - "weak and strong" sources

Later identifications, quasars - sources very distant, cosmologists licking their chops, fundamental (unknown) physics involved.

Ref: Kraus, Radio Astronomy, p. 6 - 14, p. 377, 385.
Шкловский, Cosmic Radio Waves, p. 342, 385.

B. Fundamental Catalogues.

3C Revised 178 MHz strong sources S > 9.5
  Bennett, Mem. Roy. Astron. Soc. 68, 163, 1962.
4C 178 MHz moderate sources S > 2.0
  Pilkington & Scott, Mem. Roy. Astron. Soc. 69, 183, 1965.
  Gower et al., Mem. Roy. Astron. Soc. 71, 49, 1967.
Bologna 408 MHz moderate sources S > 0.2
  Colla et al. Astr. Astrophys. Suppl. 1, 281, 1970.
BDFL 1400 MHz strong sources S > 2.0
  Bridle et al. A. J. 77, 405, 1972.
Ohio 1400 MHz moderate source S > 0.2?
  Scheer and Kraus A. J. 72, 536, 1967.
  Dixon and Kraus - 73, 381, 1968
  Fitch et al. - 74, 612, 1969
  Ehman et al. - 75, 351, 1970
  Brundage et al. - 76, 777, 1971
Parkes 400-1400-2650 moderate to strong
  Aust. J. Phys. Suppl. 7, 1969.
Etc.

Optical Identifications

3CR: Wyndham, Ap. J. 144, 459, 1966.
Bologna: Grueff and Vigotti, Astr. Astrophys. Suppl. 6, 1, 1972
Etc.

III. RADIO OBSERVATIONS AND DATA

A. Basic Measurement $I(\nu, \Omega, \text{pol.}, t)$

I = intensity, ν = frequency, Ω = solid angle, pol = polarization (4), t = time variation.

Very limited data producing challenging and chaotic physics.

Ref: Hagfors and Moran, Proc. IEEE, 58, 743, 1970.

B. Useful Techniques

1) Simple telescope - Good for integrated measures of radio sources, i.e. total flux density, integrated polarization, etc.
   Most xgal. source < 1' unresolved
   Confusion for weak sources, non-random sensitivity limits.

2) Interferometry and Aperture Synthesis - resolution $\sim 1''$ and $0\overset{''}{.}001$ in VLB. Internal structure.

Ref: Ryle and Hewish, M.N.R.A.S., 120, 220, 1960.

3) Scintillation - Flickering of a radio signal when passing through the solar plasma - analogous to twinkling. Some structure information $0\overset{''}{.}1$ to $2''$.

Ref: Cohen et al. Astrophy. J. 150, 767, 1967.

4) Lunar occultation - Disappearance of a radio source behind the sun.

Ref: Scheuer, Aust. J. Phys. 15, 333, 1962.

C. Synopsis of Observational Data

Outstanding properties of sources and correlation of sources.

1) Spectra $I(\nu)$
   a) Most sources have power law spectrum $I(\nu) \sim \nu^{\alpha}$ $-1.0 < \alpha < 0.0$ implies synchrotron radiation, power law electron energy distribution.

Fig. 1 b) Some curvature in power law behavior implies source aging, continuous or quasi continuous energy injection

c) low frequency cutoff very small sources, optically thick

c) Variability - outburst of energy into expanding clouds of relativistic electrons - time lag of maximum in spectrum.

<u>Ref</u>: Kellermann et al. Astrophy. J. <u>157</u>, 1, 1969. Basic Data.
Scheuer and Williams, Ann. Rev. Astron. & Astrophys. <u>6</u>, 321, 1968. Basic Types.
Kellermann and Pauliny-Toth, Ann. Rev. Astron. & Astrophys. <u>6</u>, 417, 1968. Variability.

2) Source Structure $I(\Omega)$

a) Most sources lie along a well-defined axis - "doubleness" antiparallel ejection, $\lesssim$ 1 to 300 kpc in size.

Fig. 2 b) Some details - emission concentration to outside, components usually connected, opaque central component, general equality of components, similar spectra.

c) Compact sources may be similar.

d) Other types ($\sim$ 20% of structures) core-halos, tail sources.

<u>Ref</u>: Fomalont Ap. J. <u>157</u>, 1027, 1969. } General properties
Mackey M.N.R.A.S. <u>154</u>, 209, 1971
Miley et al. Nature <u>237</u>, 269, 1972. Tails

3) Polarization I (pol)

- a) Mostly linear - complicated. Well ordered fields in some parts of source. 60% maximum in synchr. radiation not surpassed.
- Fig. 3. b) Depolarization at low frequency implies thermal plasma. More depol. for small sources. Some redshift effect.
- c) Circular polarization - several tenths of a percent seen in compact sources. Measure of magnetic field.
- d) Faraday rotation - thermal plasma outside of source - mostly in our galaxy.

<u>Ref</u>:	
Kronberg and Conway M.N.R.A.S. <u>147</u>, 179, 1970	DATA
Seielstad and Weiler A.J. <u>76</u>, 211, 1971	DISTRIBUTION
Strom, Nature <u>244</u>, 2, 1973.	REPOLARIZATION
Conway et al. M.N.R.A.S. <u>152</u>, 1P	C.P. DATA
Sciama and Rees Nature <u>216</u>, 147, 1967.	C.P. THEORY

4) Variability I(t)

- a) Systematic behavior of total power - injection of
- Fig. 4. electrons, opaque source - polarization changes.
- b) Fast Motions??

<u>Ref</u>:	
Aller, Ap. J. <u>161</u>, 1, 1970	POLARIZATION
Rees, M.N.R.A.S. <u>135</u>, 345, 1967.	MODEL

5) Identifications with optical objects.

- a) Distance obtained from optical redshift.
- b) Strong sources associated with elliptical type galaxies or blue objects - quasars. Spiral galaxies are weak emitters.
- c) It is impossible to distinguish the radio properties between a galaxy or quasar. Further, radio quiet galaxies and blue objects do not differ optically from strong radio galaxies and quasars.

IV. THE LIFE AND DEATH OF A RADIO SOURCE

A. General Stages

1) Energy Production
2) Energy conversion to relativistic particles
3) Collimation into axially symmetric clouds and expansion
4) Confinement of clouds, further energy sources.

B. Energy Production

1) How much energy in a radio source?

$S = 10$ f.u. $D = 1000$ Mpc. What is L = total radiated power.

$L = 10^{-25}$ w m^{-2} Hz^{-1} x $(3 \times 10^{25}\ m)^2 \times 10^{11}$ Hz $= 10^{37}$ w $= 10^{11}\ L_{\odot}$

E_e = energy of relativistic particles (10^6 yr. lifttime)

$E_e = L \times 10^6$ yr x 3×10^7 sec/yr $\approx 10^{50}$ joule

E_T = total energy includes energy in all particles and fields.

$E_T = 100 \times E_e$ $\quad E_T = 10^{52}$ joule $= 10^{59}$ erg $=$

$$E_T \approx 10^5\ M_{\odot}\ c^2.$$

i.e. need to convert 0.1% of a galaxy into energy!!

Ref: Mackay, M.N.R.A.S. 145, 31, 1969 Typical Calculation.

2) Where does energy come from.

? ? ? ? ? ? ? ? ? ? ? ? ? ?

Guesses: Gravitational, i.e. collapsing massive objects, dense star cluster producing many supernovae, blue hole.

Ref: De Young and Burbidge Comments on Ast. Vol. V No. 2 1973.
- Good summary.

C. Energy Conversion to Relativistic Particles

??? Flares, Pulsar Radiation

Ref: Burbidge Ap. J. 159, L105, 1970. Pulsars
Sturrock and Barnes Ap. J. 176, 31, 1972. Plasma Instabilities

D. Radio Source Collimation and Ejection.

1) Collimated by external field. "Simple" plasma considerations do not produce compact components.

2) Galactic magn. field - twisted field around rotat. axis mag. tongues guide electrons.

3) Synchr. Compton radiation: low freq. waves due to pulsars cavity effect.

4) Massive bodies, slight shots; instability of multibody systems ejected components.

5) Geometry of fast ejection. If $v \sim c$ what happens to a double.

6) Radio-optical correlations. Major axis of elliptical galaxy and radio structure. Random, equatorial ejection?

<u>Ref:</u>	v.d. laan, M.N.R.A.S. <u>126</u>, 535, 1963	Ext. Field coli.
	Piddington, M.N.R.A.S. <u>148</u>, 131, 1970	Wound Mag. field
	Rees, Nature <u>229</u>, 312, 1971.	Synchr. Compton
	Saslaw et al. in press	Sling shots
	Ryle and Longair M.N.R.A.S.<u>136</u>, 123, 1967	} Velocity of ejection
	Mackay ___ <u>162</u>, 1, 1973	
	Mackay ___ <u>151</u>, 421, 1971	Radio-opt. correl.

E. Confinement and Energy Replenishment

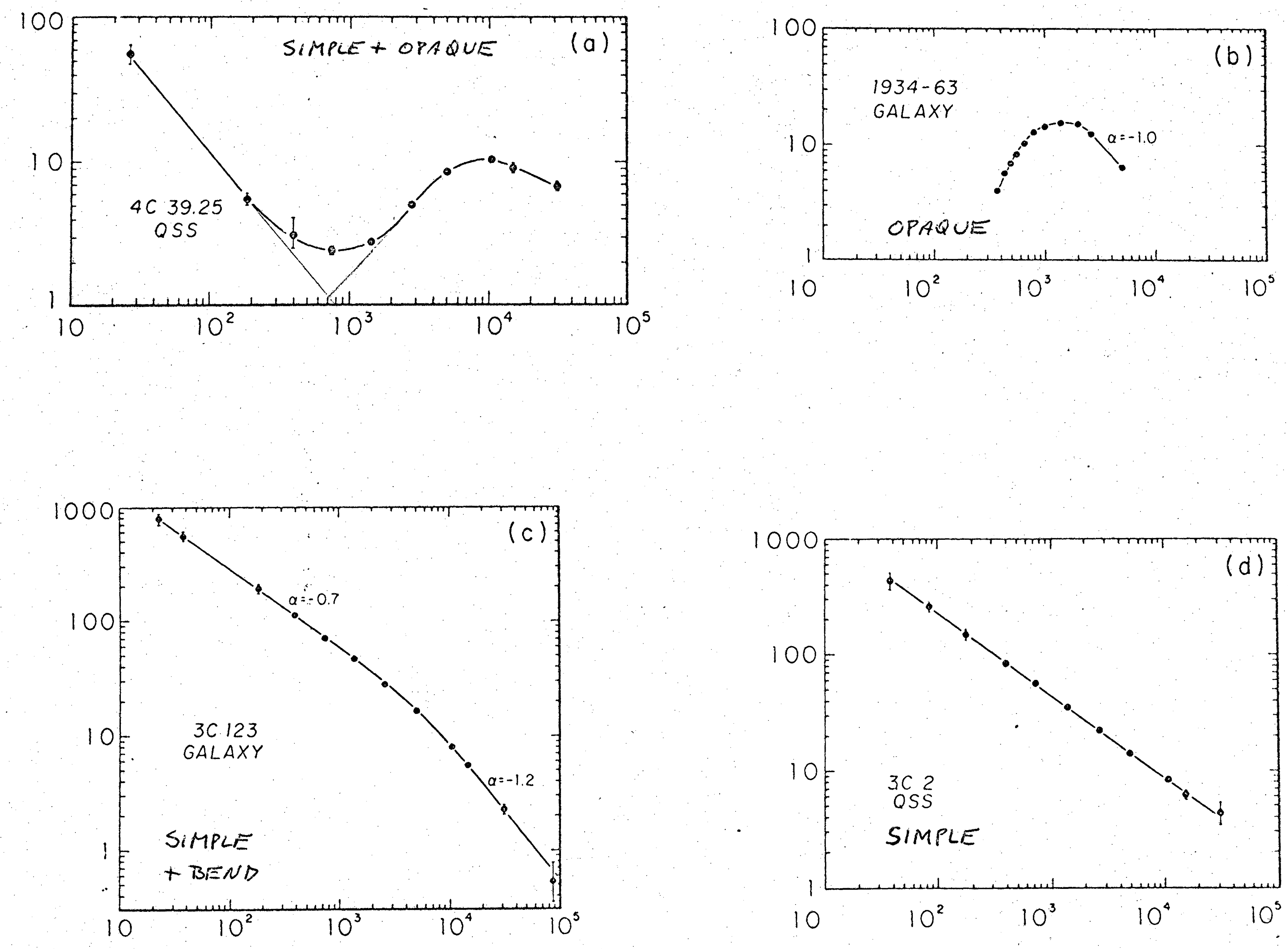
1) Self grativation. Massive objects keep components together. Can provide continuous energy source. Sources have fine structure. But lifetime too short, too many massive objects needed for uniform radio sources.

2) Ram pressure. Confinement due to supersonic motion of source by intergalactic medium. General radio shapes fit theory. Tail sources also suggest external medium. But density is high $\sim 10^{-28}$ gm cm^{-3}, enough for universe closure. Expansion losses too high.

3) Low freq. waves. Cavity formed by E.M. waves. Replenishment natural, but cavity must be plasma free except at edge.

Ref:	Burbidge, Nature <u>216</u>, 1287, 1967.	Massive objects.
	De Young and Axford Nature <u>216</u>, 129, 1967	Ram pressure.
	Rees, Nature <u>229</u>, 516, 1967.	Low freq. waves.

FIG. 1



(a)
SIMPLE + OPAQUE
4C 39.25
QSS
100
10
1
10
10^2
10^3
10^4
10^5
(b)
1934-63
GALAXY
α=-1.0
OPAQUE
100
10
1
10
10^2
10^3
10^4
10^5
(c)
α=-0.7
α=-1.2
3C 123
GALAXY
SIMPLE
+ BEND
1000
100
10
1
10
10^2
10^3
10^4
10^5
(d)
3C 2
QSS
SIMPLE
1000
100
10
1
10
10^2
10^3
10^4
10^5

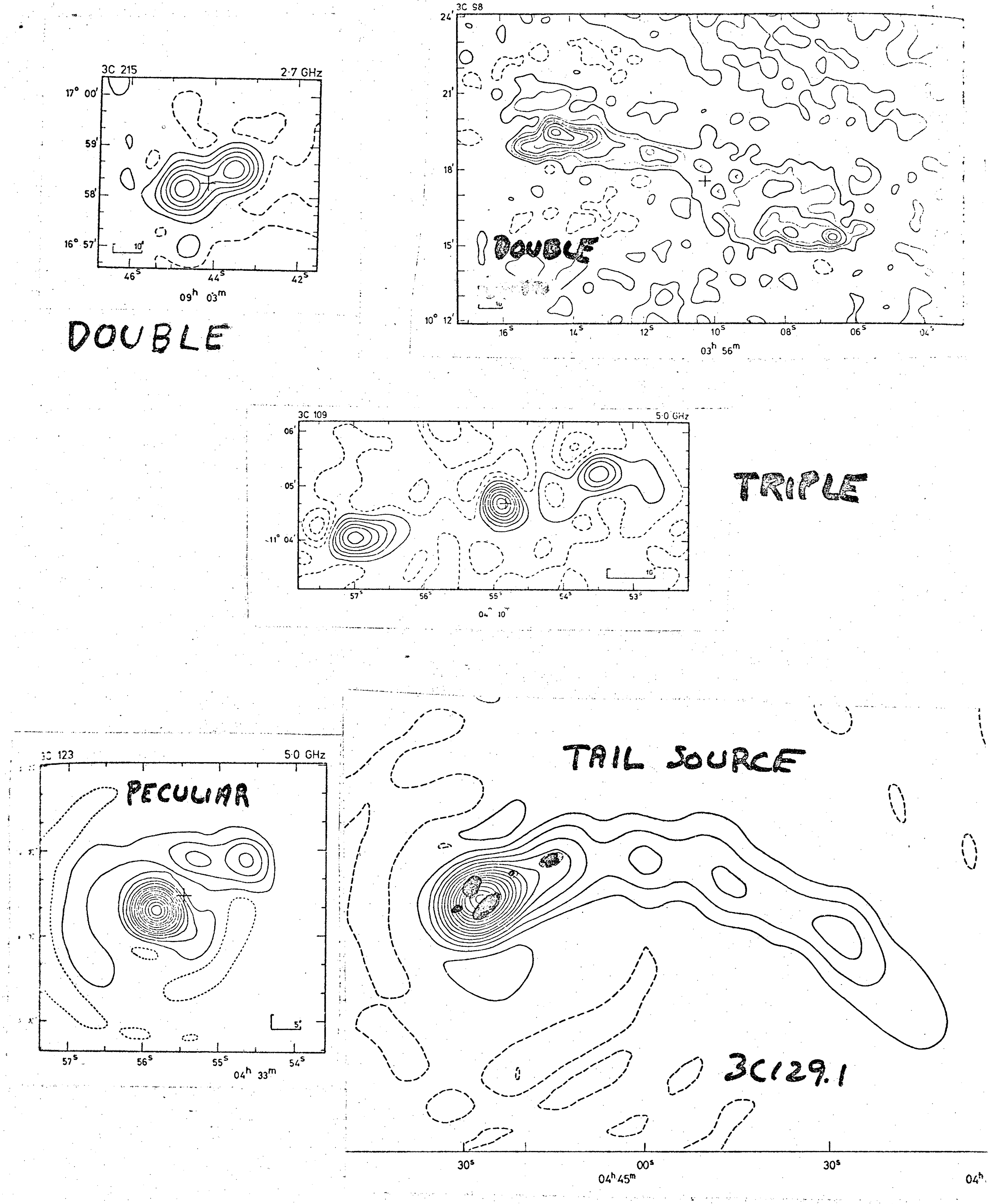
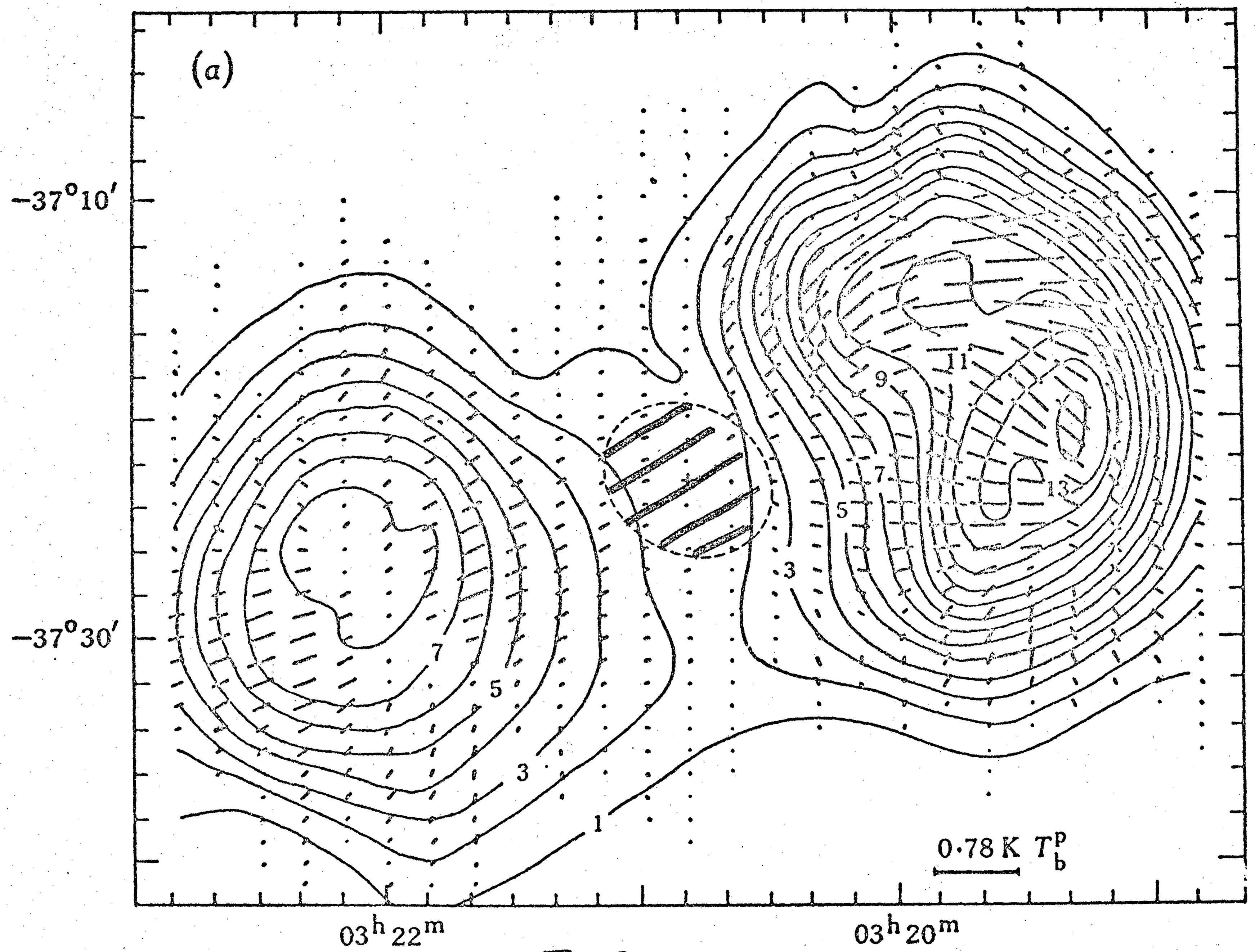

3C 215
2·7 GHz
17° 00'
59'
58'
16° 57'
10"
46s
44s
42s
09h 03m
DOUBLE
3C 98
24'
21'
18'
15'
10° 12'
10"
16s
14s
12s
10s
08s
06s
04s
03h 56m
DOUBLE
3C 109
5·0 GHz
06'
05'
-11° 04'
10"
57s
56s
55s
54s
53s
04h 10m
TRIPLE
3C 123
5·0 GHz
PECULIAR
5"
57s
56s
55s
54s
04h 33m
TAIL SOURCE
3C129.1
30s
00s
30s
04h 45m
04h

FIG. 2

FIG 3



FORNAX A

FIG. 4

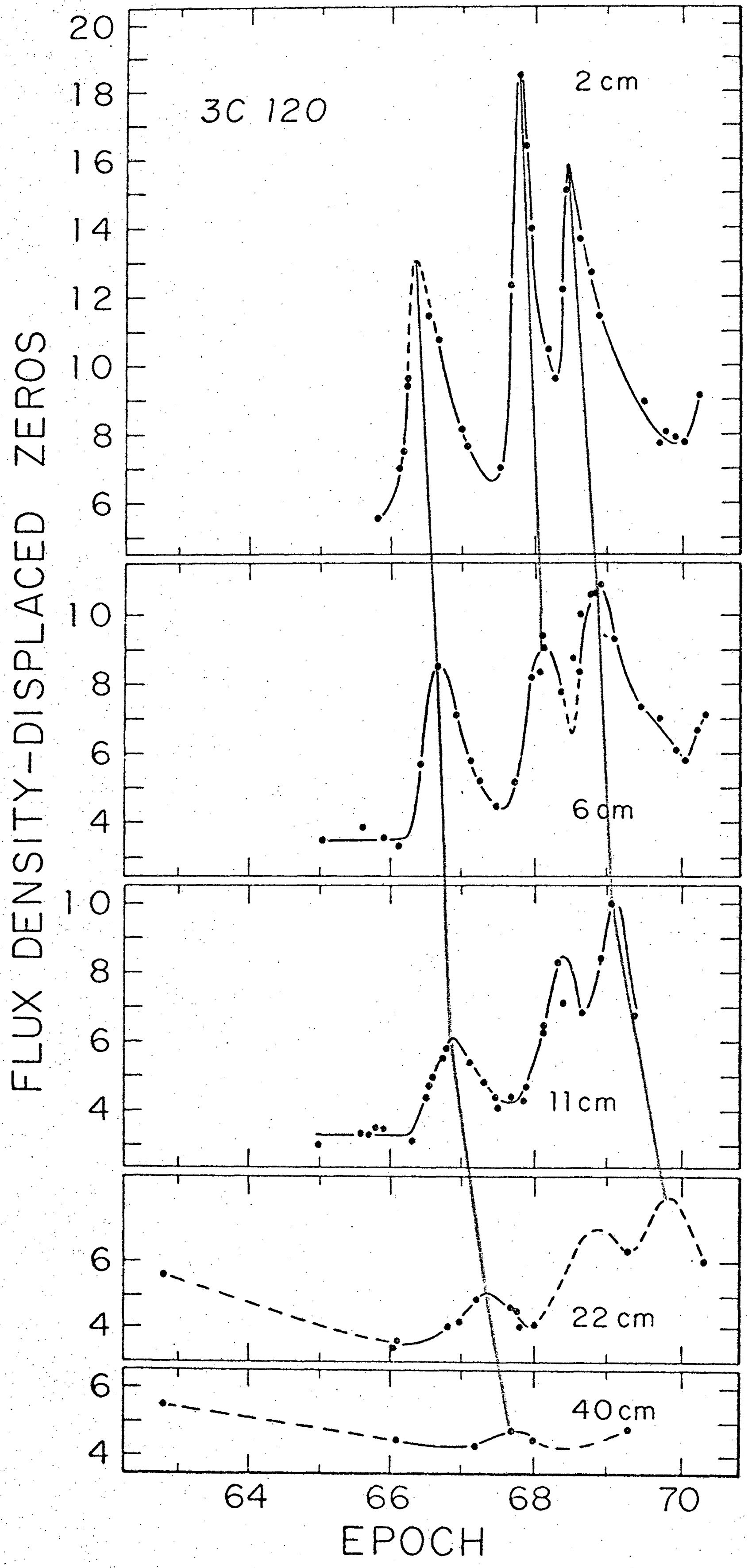

3C 120
2 cm
6 cm
11 cm
22 cm
40 cm
FLUX DENSITY-DISPLACED ZEROS
6
8
10
12
14
16
18
20
4
6
8
10
4
6
8
10
4
6
4
6
64
66
68
70
EPOCH

FIG 4.