Summer 1970 - NRAO

LFRA. <40 MHz.

RA began here. Jansky 20.5 MHz.
LF background continuum $T_B \sim 10^4$ K.
Discrete sources bright at LF, but radio astronomers soon realised need for resolving powers << 1°.

1° resolution at	1000 MHz	~20 metre aperture
	100	200
	10	2000

This alone encouraged people to go to frequencies ≳ 100 MHz. The decrease in source brightness was no great problem with available sensitivities, whereas huge (≳1 mile) antenna structures were.

Also ionospheric phenomena discourage use of frequencies << 100 MHz
The ionosphere is a plasma electron densities $\sim 10^5$/cc
height 80 - 500 km above ground.

Refractive index of plasma $n^2 = 1 - \frac{f_c^2}{f^2}$

$$f_c^2 = \frac{N_e e^2}{4\pi^3 \varepsilon_0 m}$$

Typically 2 - 10 MHz, but range can be ≃ 40 → 1.
For $f \gg f_c$, $n \sim 1$ and effects of ionosphere on radio wave propagation are small. But for low f, departures of n from unity become large.

Electrons in ionosphere produced by ionizing flux of solar UV (X) and particles. Produced in daytime hours. Recombine by collision. At night, ionizing flux removed, recombination.

__Absorption__ worst at low levels where collisions frequent.

D layer ~ 3 to 5dB typically in daytime in summer at sunspot minimum at 10 MHz.

To get low absorption. Work AT night (no D layer)
in winter (small day length)
sunspot minimum (least particle flux).

Absorption as low as 0.3dB at night at 10 MHz.

__Refraction.__

Gradients in electron density → regular refraction

More electrons over equator and poles.

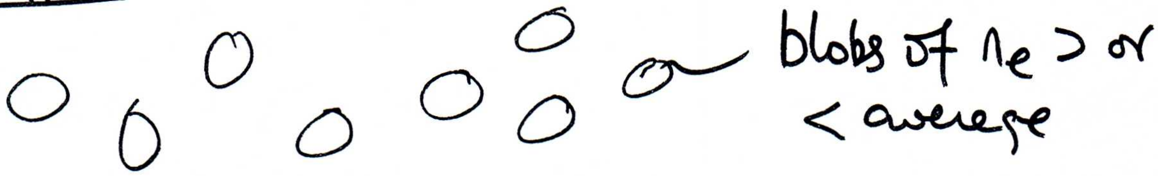
↑ direct ioniz — ↑ dumping particles.

up to 1° at 10 MHz, on zenith, southwards.

Spherical refraction up to 2° northwards at hi Z.

Get around by multibeaming to determine refraction.

__Irregular effects.__



Plane wave comes out corrugated.

→ amplitude variation on ground.
variation in apparent position. ~20 arc min rms at 10 MHz.

As blobs drift → scintillations or "twinkling".

Interference Ionospherically reflected.

~~[illegible]~~ Japanese fishing boats
Communist Chinese trying to
jam WWVB.

Band utilisation $f \sim 3f_0$ $\left(n^2 = 1 - \frac{f_0^2}{f^2}\right)$.

$f_0 = \frac{Ne^2}{4\pi^2 \varepsilon_0 m}$

Need. Winter
Night
Sunspot minimum
Small gradients or reflection analysis.
Smooth ionosphere (1 in 10^3 over ~ 2km scale).
No-one in band.

Maximum ~~[illegible]~~ utilization of observing time required. Multibeam in δ.

BW ~ 8kHz. at 10MHz.

10MHz array. 2°.3 beam
~ 150 sources. + Galactic bgnd map.

DISCUSS REASONS FOR TRYING LF, PLASMAS ETC.

Results. 1. Source spectra
High b^{II}.

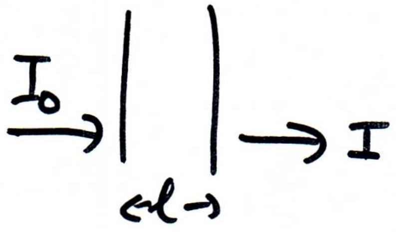
Strong correlation between α decr. at LF. and IPS.
19 sources known at 178 to have >50% <1" arc. All ~~[illegible]~~ have α decr.

60% of IPS sources → α decr at LF
30% non IPS → α decr (hi-B?)
50% of non-IPS → S spectra.
~~[illegible]~~ ~15% of IPS → S spectra

Thermal plasma

Radiation waggles electrons. When near $\oplus$ ion, some of energy transferred to electron is not reradiated, but transferred to $\oplus$ ion. Can think of inelastic collisions between e and $\oplus$ while e is vibrating. Close Coulomb interaction needing quant. mech in fact.

Linear absorption coefficient $\quad I = I_0 e^{-kl}$



$$k = \frac{\text{const. } T_e^{-3/2}}{\nu^2}\left[17.7 + \ln \frac{T_e^{3/2}}{\nu}\right] \times N_e^2 .$$

(Scheuer M.N. 120, 131 (1960)).

Optical depth $\tau = \int k\,dl \;\propto\; \dfrac{N_e^2 L T_e^{-3/2}}{\nu^2}$

$$I = I_0 e^{-\tau}.$$

τ is high for
i) dense plasmas
ii) cool plasmas
iii) low frequencies.

Relativistic plasma and B.

Ginzburg, Sazonov & Syrovatskii
Sov. Phys. Uspekhi 11, 34 (1968).

$$k = \text{const. } f(\gamma)\, N_0\, B^{\frac{2+\gamma}{2}}\, \nu^{-\frac{4+\gamma}{2}}$$

where relativistic electrons $N(E) = N_0 E^{-\gamma}$.

$$\left.\begin{array}{l}\text{Dense plasmas}\\ \text{High } B\\ \text{low frequencies}\end{array}\right\} \rightarrow \text{hi } \tau.$$

Reasons for building ground-based LF telescopes circa 1965-5.

① SSA in eg sources ~~QSOs~~.. Measure ν_{max}.

For simple source model $\nu_{max} \cancel{\propto} 0.782\, S_{fu} \sqrt{B_\perp}\, \theta^{-2} (1+z)^{1/2}$

$\times (0.85 + 2.63\alpha + 0.33\alpha^2)$.

ν_{max} = turnover S_{max} = max S at ν_{max}.

$B_\perp$ in μgauss. θ in sec arc.

Know θ from higher ν → B if θ not θ(ν)

Guess B → θ ($\theta \propto B^{1/4}$).

Then use Synchrotron theory → total energies.

② Galaxy.

Bright (optical) H II regions should be opaque at LF.

Absorb galactic background. Opacity → T_e

Absorption of discrete sources → method of studying diffuse ionization in galaxy, too faint to see optically.

Gas which is only just visible on Palomar prints is completely opaque at 10 MHz.

Need to study thermal balance of interstellar medium if to understand cloud formation → star formation.

Fundamental problem of astronomy!

2 Also, shot in the dark. (4) 6.

Every new freq. range opened up by RA has → new objects or new stages in evolution of previously known objects. What would show at LF?

Anything bright at LF, not at higher F. → steep spectra.

Synchrotron and ICE losses $-\frac{\partial E}{\partial t} \propto E^2$.

Old synchrotron sources. Extragalactic fossil galaxies?

Or anything with $N(E) \propto E^{-\gamma}$ and hi γ.

$(\gamma = 2\alpha + 1)$.

<u>Problems.</u>

① Getting resolving power.

10 MHz telescope with resolution of the NRAO 2-foot has dimension ~ 3/4 mile!

T-antennas. Mills + but why phase more than you have to? Costain, Lacey, Roger, IEEE Trans AP, <u>AP-17</u>, 162 (1969).

Steer in δ with phase (delay) cables. Meridian transit.

② Ionosphere. Plasma [illegible] affects propagation of waves.

Refractive index and absorption coefficient.

Field strengths typically 10 gauss.

Some $B<10^{-5}$ gauss.

Total energies of QSO's and galaxies ~ same. $10^{60\pm2}$ erg.

<u>S spectra distribution.</u>

Williams & Bridle,
Obs. <u>87</u>, 280 (1967)

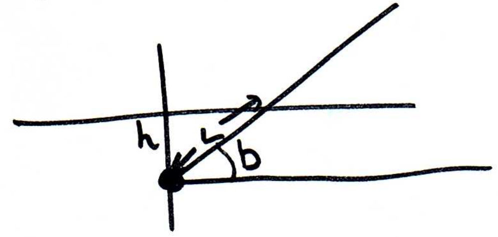
Frequency selection. gaussian → gaussian'.

At LF find new population of steep spectra. Many of these occur in clusters of galaxies. Possibly adiabatic expansion slowed by intergalactic medium. Source stays luminous long enough for synchrotron losses to steepen spectrum. Outside cluster, adiabatic expansion is easier, source dissipates while spectrum still un-aged?

Galaxy.

To find gross features of electron distribution, assume n_e horizontally stratified. (n_H is).

Derive $\tau(10)$ from e-g source spectra, avoiding curved spectra and compact sources. Find $\tau(10)$ higher at low-b^{II}.



$$\tau = \int k\,dl = \bar{k}L$$

$$= \bar{k}h\,\mathrm{cosec}\,b.$$

Plot τ vs cosec b → $\bar{k}h$ optical depth of galactic pole

At 10 MHz, $\bar{k}h = 0.10 \pm 0.02$.

For galactic sources, also find $\tau = k\ell$
$\uparrow$ known.

$\therefore$ can find $\bar{k}$ $= 0.34 \pm .07\ \mathrm{kpc}^{-1}$. average.

Thus $h = 300 \pm 100$ pc.

Much thicker than equivalent h of neutral 21 cm emission.

i.e. $\frac{n_e}{n_H}$ increases with height above plane, [redacted]

Presumably then T increases with height above plane.

Characteristic T_e in plane?

$$\bar{k} \propto \overline{n_e^2 T_e^{-3/2}}$$

Bridle & Venu.
Nature, 224,
545 (1969).

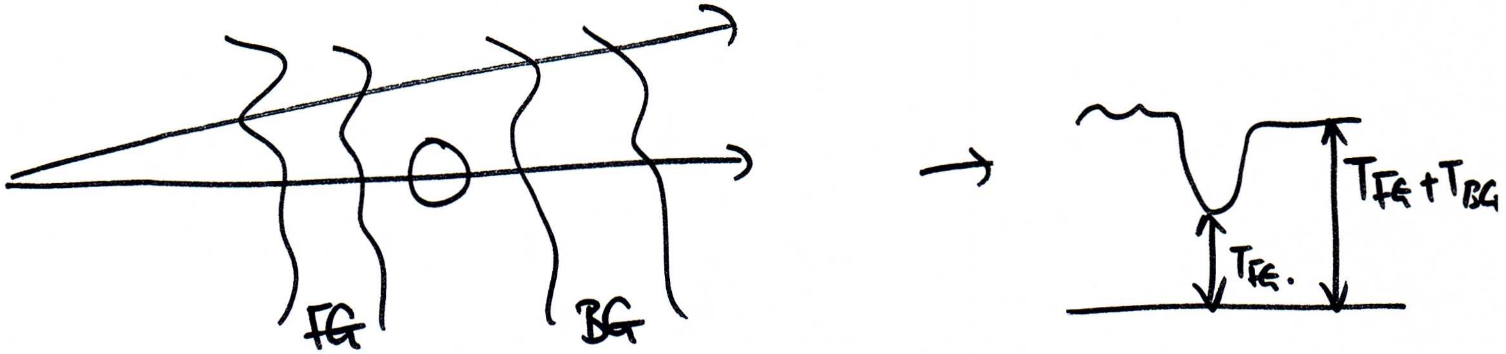
From pulsars, know $\bar{n}_e \sim 0.02\ \mathrm{cm}^{-3}$.

$$\overline{n_e^2} = \frac{(\bar{n}_e)^2}{\xi}$$

$$\xi \sim 0.1 \rightarrow \bar{T}_e \sim 1000\ \mathrm{K}.$$

Much cooler than expected from UV heating, suggests that main heating mechanism is cosmic ray flux colliding with H atoms. Consistent with 21 cm absorption studies of interstellar medium, and picture of dense cool clouds embedded in rarefied hot material. Clouds are where cooling became efficient → thermal, rather than gravitational, instability starts cloud collapse.

Other galactic studies. HII regions in absorption against bgnd.



If it fills beam, can measure T_{FG}.

Know distance to HII region, from optical photometry.

Hence know T_{FG} per parsec, or emissivity of FG material.

$$\eta(\nu) \propto B_\perp^{\frac{\gamma+1}{2}} N_0 \nu^{-(\gamma-1)/2} .$$

$\therefore$ Can measure $N_0 B_\perp^{\frac{\gamma+1}{2}}$. $\gamma = 2\alpha+1$.

If N_0 estimated from local cr electrons → $B_\perp \sim 10^{-5}$ gauss.

$B_\perp$ from Faraday rotation & Zeeman effect $\sim 10^{-6}$ gauss for $B_{\parallel}$.

(Factors of 2 neglected here).

Possibility. ① N_0 underestimated locally.

② B is folded

③ Both B and N_0 vary thru galaxy.

Higher-resolution will → more regions, investigate distribution of η through galaxy. Spiral arms?

The Crab Nebula.

Lunar occultation at 26 MHz → compact source in Crab (Andrew et al, Nature, 203, 171 (1964))

Position measured by Gower (Nature, 213, 1213 (1967))

α in excellent agreement with pulsar.
δ also in agreement but ± several min arcs not v. significant.

At VLF, pulsar pulses dispersed so they overlap in few kHz bandwidth. Continuum source?

Spectrum of Crab, corrected for interstellar absorption, rises at LF. → decompose into two spectra . Bridle, Nature 225, 1035 (1970)

$\alpha = 1.76$ for compact object, similar to pulsar spectrum.

VLB at 22 MHz → θ increases with decr ν. Probably due to interstellar scattering entirely.

$\theta_{\rm true}$ probably $< 0''.1$ sec arc. $T_B \sim 3 \times 10^{15}$ K

Then either $B \ll$ ~~10^{-8}~~ 6×10^{-8} gauss, $E > 4\times10^{51}$ ergs in electrons / or not electron synchrotron radiation. Latter is much more likely. Only source of continuum we can be reasonably sure not an electron synchrotron source.

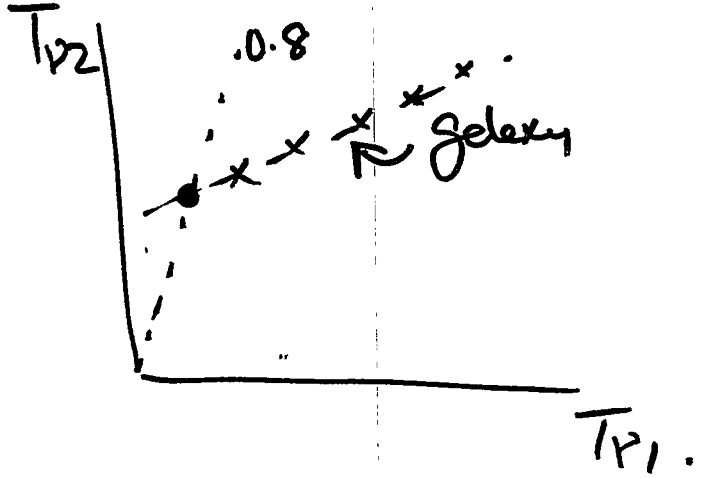
Proton synchrotron $B < 0.4$ gauss, $B > 1.5 \times 10^{47}$ ergs.
But no electrons could be in region, as ν_G for $B \sim 0.4$ gauss is only 1.2 MHz. Electrons would absorb proton radiation.

Still a puzzle? Coherent mechanism?

Integrated emission of extragalactic objects.

Background of all unresolved sources out to $z = \infty$. Isotropic, see the galactic radiation against it.

Spectrum steeper than that of Galaxy, so becomes relatively more important at LF. Can measure it by absolute observations of background brightness.



Provides important constraint on cosmological interpretations of the source counts. Cannot invoke a cosmology to explain $N(S)$ if the cosmology would imply more than the measured integrated brightness.

Possible future experiment. Correlation of LF spectra with z or with optical absorption lines.