ASTRONOMY GROUP SEMINAR
1970

Low frequency r.a.

"Low" means low enough for ionospheric effects to be important.

Ionosphere plasma $Ne \sim 10^5$/cc, height $\sim 80-500$ km/sec. Maintained during daytime by solar UV, particles.

Index $n^2 = 1 - f_p^2/f^2$ [illegible] $f_p^2 \propto \frac{Ne\, e^2}{m}$

Absorption coefficient $k \propto \frac{f_p^2 f_c}{f^2}$ if $f \gg f_B$ ~~f_c = collision frequency~~
~~f_B = gyro~~
$f \sim f_B$, gyromagnetic splitting → diff't k's. ~~$\pm$ = $\overset{o}{e}$ modes.~~

lide	Ne profiles show	Ne highest	DAY	SUMMER	SOLAR MAX
			↕	↕	↕
		least.	NIGHT	WINTER	SOLAR MIN

Absorption worst in D layer where f_c high. D layer decays at night, residual absorption is F layer.

lide 10 MHz absorption ~3dB daytime to < 0.2dB night in 1965-66.

Refraction ① Spherical $\propto h \frac{f_p^2}{f^2} \tan z \sec^2 z$ small at night.

② NS wedge $\propto h . \frac{1}{f^2} \frac{\partial f_p^2}{\partial \lambda} \sec^2 z$ equator - aurora

③ EW wedge $\propto h . \frac{1}{f^2} . \frac{\partial f_p^2}{\partial \Lambda} \sec \delta \sec z$ Sunrise Sunset

10 MHz night. ① $\lesssim 0.1$ deg.
② ~ 0.5 deg.
③ ~ 3° sunrise/sunset.

Scintillation Irregularities in phase → amplitude fluctuations below.
Drifting screen → time fluctuations.
Up to 100% fluctuations when Ne irregularities large.

Slide Cyg A observing conditions.

Two solutions to these problems

- ① Ground-based patience
- ② Satellite based brute force — put telescope above ionosphere.

Both have contributed appreciably in last 3 years.

① Bridle, Purton, Andrew	10 to 38 MHz arrays
Erickson, Cronyn, Viner	26 MHz
Costain, Roger, Lacey	22 MHz
Reber	2.1 MHz
Bazelyan, Benediktov, Braude,	10 – 40 MHz

② Goddard Space Flight Center RAE-1
Canadian Alouette 1 and 2.

Will discuss (if time)

A. Spectrum of the nonthermal background

→ 1. Nonthermal emission from our Galaxy, emissivity and $\langle B_\perp \rangle$ of local region.

2. Isotropic nonthermal extragalactic background.

B. Diffuse ionization of interstellar gas

A. Nonthermal emission background. At HF brightest towards M.Way.
Supposed synchrotron emission from cosmic ray electrons in interstellar B.

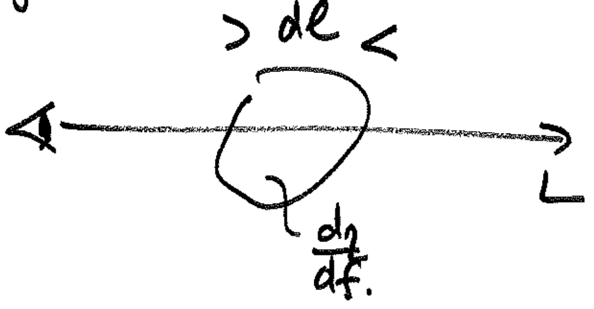
Single electron $\frac{dP}{df} \propto F(f/f^*) B_\perp$ $\qquad f^* \propto B_\perp E^2$

Volume spectral emissivity of space $\frac{d\eta}{df} \propto \int \frac{dP}{df} dn$

For power law electron spectrum $dn(E) = kE^{-\gamma} dE$ — + random B isotropic e flux

$$\frac{d\eta}{df} \propto a(\gamma) k\, B_\perp^{\left(\frac{\gamma+1}{2}\right)} f^{-\left(\frac{\gamma-1}{2}\right)}$$

Spectral intensity $\frac{dI}{df} \propto \int_0^L \frac{d\eta}{df}\, dl$



Potentially observable quantity is sky brightness temperature

$$T_b \propto \frac{dI}{df}\cdot\frac{1}{f^2} \quad \underline{\text{should be}} \propto f^{-\left(\frac{\gamma+3}{2}\right)} \propto f^{\beta} \text{ say.}$$

So in principle, we measure T_b for different frequencies in same direction.

Find $T_b(f) \to \beta$. $\beta = \frac{\gamma+3}{2} \to \gamma$.

In fact find spectrum <u>not</u> a power law. β must be $\beta(f)$

∴ Electron spectrum cannot be power law γ must be $\gamma(E)$ unless absorption has set in.

If we convolve $\gamma(E)$ with $\left(\frac{dP}{df}\right)$, we can predict $\beta(f)$ for given $B_\perp$

Along a line of sight, if electron population homogeneous $\to \langle B_\perp \rangle$.

Compare $\beta(f)$ and $\gamma(E)$, can <u>deduce</u> $\langle B_\perp \rangle$.

Alternatively, if we can determine L for a given line of sight

$$\left\langle \frac{T_b}{L} \right\rangle \to \left\langle \frac{d\eta}{df} \right\rangle \to \left\langle k B_\perp^{\frac{\gamma+1}{2}} \right\rangle$$

If k known from local cosmic ray flux, also $\to \left\langle B_\perp^{\frac{\gamma+1}{2}} \right\rangle$.

Two ways of measuring $B_\perp$.

Cautionary tale for non-observers.

What you <u>measure</u> is antenna temperature

$$T_A = \frac{\iint_B T_b(\theta,\phi)g(\theta,\phi)d\Omega + \iint_S T_b(\theta,\phi)g(\theta,\phi)d\Omega + \iint T_G(\theta,\phi)g(\theta,\phi)d\Omega}{\iint_{4\pi} g(\theta,\phi)\,d\Omega}$$

B = main beam
S = sidelobes
G = ground radiation.

$$T_A = \langle T_B \rangle \frac{\Omega_B}{\Omega} + \langle T_S \rangle \frac{\Omega_S}{\Omega} + \langle T_g \rangle \frac{\Omega_G}{\Omega}.$$

Thus T_A contains smoothed T_b contrib from $\begin{matrix}B\\S\end{matrix}$

smoothed T_G contrib.

Cannot compare any old T_A's directly!

At best, $\langle T_B \rangle$ is a weighted average of T_b over beam pattern of telescope.
If two antennas smooth T_b ~ same way (same beam pattern), then $\langle T_B \rangle$ comparison point-by-point on sky → smoothed sky distribution of β, $\langle \beta \rangle$.

However, must take into account $\langle T_S \rangle$, $\langle T_g \rangle$.

If T_b in sidelobes small, or $\iint_S g(\theta,\varphi)\,d\Omega$ small, $\langle T_S \rangle \ll \langle T_B \rangle$

Similarly for T_g.

At high freqs, $\langle T_g \rangle \approx \langle T_B \rangle$ because ground bright and sky cool.

At low freqs $\langle T_g \rangle \ll \langle T_B \rangle$.

Can arrange for $\frac{\langle T_S \rangle}{\langle T_B \rangle}$ to be nearly independent of freq. if $\frac{\iint_S g(\theta,\varphi)\,d\Omega}{\iint_B g(\theta,\varphi)\,d\Omega}$ ~ same for antennas used at all freqs.

Only way to ensure this is to replicate $g(\theta,\varphi)$ exactly.

To do this need, [illegible] geometrically scaled antennas. All significant physical features scaled as $\frac{f_2}{f_1}$ going $f_1 \leftrightarrow f_2$. With reasonable collecting area, this is more practicable at LF where dipole arrays can be scaled than at HF where you must scale large paraboloids.

Cambridge Group Bridle, Purton, Howell 13.15 — 610 MHz.

At each point in sky $\frac{T_A(f_1)}{T_A(f_2)} \to \frac{\langle T_{b1} \rangle}{\langle T_{b2} \rangle} \to \langle \beta \rangle$.

Find $\langle \beta \rangle$ varies across sky.

$\langle \beta \rangle$ is greatest in direction of minimum T_A (T_b). Slide

How to interpret?

Superimpose anisotropic galactic component with index β_a on an isotropic extragalactic nonthermal background with index β_i.

To → the observed variation of β across sky β_a must be $> \beta_i$. How to separate? Can do this by plotting T_A at one frequency against T_A at same point in sky at another frequency. Slide.

Isotropic component → a point.

If just one β_a, then all other points lie on a line of slope $\left(\frac{f_2}{f_1}\right)^{\beta_a}$

going through the point representing the isotropic component.

Slope of line → β_a with no further assumptions.

Then can find T_i if can assume β_i.

T-T plot of scaled antennas data Slide

Variations in β_a across sky. Divide into 2 regions → spiral arm line of sight
inter-arm
→ lines Slide

Spiral arm spectrum is curved Slide

$$\frac{n(r_0)}{n(\infty)} = e^{-KR/D}.$$

KR depends on bulk outward velocity of solar wind. D is a diffusion coeff for particle in solar magnetic field. Varies with E. KR = number, best value 0.9, 0.5 - 2.

Fit to shape of demodulated electron spectrum $\xrightarrow{\text{best}}$ 7-8 μ gauss for $\langle B_\perp \rangle$ (KR ~ 0.6) Slide

Could also be KR ~ 1, B ~ 5 μ gauss.

The Δβ observed would → slightly lower $\langle B_\perp \rangle$ in interarm.

"Secondaries" are the expected emissivity from 5-6 g/cm² cosmic ray nuclei collisions → π mesons → μ, e.

Note the offset from (0,0) in the T-T plots. This → extragalactic component.

In universe with R-W type metric

$$ds^2 = c^2 dt^2 - R^2(t)\left[\text{[redacted]}\, dr^2 + \left(\frac{\sin Ar}{A}\right)^2 (d\theta^2 + \sin^2\theta\, d\phi^2) \right]$$

A = curvature of space now (= 0 for steady-state)

Then brightness temp. observed

s. index of rad.

$$T(f_{obs}, t_{obs}) = \frac{c^3}{2kf_0^2} \int_{t^*}^{t_{obs}} \eta\,[illegible](f_{obs}, t) \left[\frac{R(t)}{R(t_{obs})}\right]^{3+\alpha} dt.$$

t^* defined by $R(t^*) = 0$.

Here $\eta(f_{obs},t)$ is the average volume emissivity of the universe at a frequency f_{obs} at cosmic time t.

$$\eta(f_{obs},t) = \int_0^\infty \rho(P,f_0,t)\,P\,dP \quad \text{where } \rho(P,f_0,t) = \frac{dn}{dP}$$

ρ will be a function of t in an evolutionary universe. Can have galaxy density or luminosity/galaxy evolution. Not possible to distinguish them. Can determine $\rho_{local}(P,f_0) = \left(dn/dP\right)_{locally}$ by direct observation. Cosmology then $\rightarrow$ $\rho(P,f_0,t)$. Given $\rho(P,f_0)$ <u>now</u>, different cosmologies $\rightarrow$ different integrated emissions. Of particular interest are evolutionary models invoked to explain the source counts.

$$N(>S)S^{3/2} = \int \rho(P,f_0)\,P^{3/2}\left\{\frac{2Ar_p - \sin 2Ar_p}{4\sin^3 Ar_p}\right\}(1+z_p)^{-3/2(1+\alpha)}\,dP.$$

z_p and r_p are values for a source with radio luminosity P at the limiting flux density S.

Cambridge: $(1+z)^6$ evolution, cannot continue beyond $z \sim 2$ or 4 without violating T_i for the integrated emission.

Large contribution to T_i can come from the week radio sources, ~~[illegible]~~ low P, high ρ. Week radio galaxies $P_{178} \sim 10^{22}$ w/Hz/ster/gal

$\rho \sim 2\times10^{-3}$ gal/Mpc^3.

If these have $\rho(t)$ evolution invoked to explain number count, $T_i \sim 200$ K !! at 178 MHz. Exceeds minimum brightness (~ 65 K) Hence they do not.

For steady state, $\rho(t) = $ const., $R(t) = e^{Ht}$, $t^* = -\infty$

$$T_i \sim 1.9 \text{ K at } 178 \text{ MHz}$$

Model of background: 30±7 K at 178 with mean spec. of strong sources.
$\beta \sim 2.7$, increasing to ~ 2.9 at ~ 10 MHz.

Anisotropic galactic background $\beta \sim 2.4$.

Slide Take 178 MHz maps, ~ 2°.5 resolution → Predict $T_b(10)$ on the model.

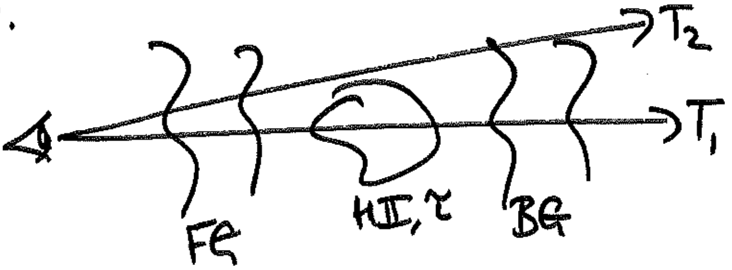
Slide Compare observed $T_b(10)$. Plot ratio $\frac{T_b(10)\,\text{obs}}{T_b(10)\,\text{pred}}$ point-by-point.

Features ① Massive absorption by discrete HII regions
Slides ② Absorption along galactic equator $l \lesssim 60°$ – continuous.
③ Peculiar spectrum of N.E. Spur.

Slide Absorption coefficient of plasma $k \propto N_e^2 T_e^{-3/2} f^{-2}\left[17.7 + \ln \frac{T_e^{3/2}}{f}\right]$

At 10 MHz, both discrete HII regions and dilute interstellar plasma become opaque.

For HII region, $T \sim 8000$ K,
$\tau \sim 7\times10^{-3} E$ at 10 MHz.
$\tau \sim 1$ for $E \sim 145$



$$T_{b1} = T_{FG} + T_e(1-e^{-\tau}) + T_{BG}e^{-\tau} \qquad T_2 \sim T_{FG} + T_{BG}$$

For large τ, $T_{b1} \to T_{FG} + T_e \to T_{FG}$
$T_{b2} \to T_{FG} + T_{BG}$.

If HII region fills beam with large τ, $T_{b1} \to T_{FG}$.

If know distance to HII region, can find $\left\langle \frac{T_{FG}}{L} \right\rangle \to \left\langle \frac{d\eta}{df} \right\rangle$.

$l^{II} \sim 140°$. IC1795, 1805, 1848 at 10 MHz. Contours of 100,000 K. Slide

$T_{FG} \sim$ 85 to 140,000 K allowing for spillover and T_e
L ~ 2.0 ± 0.1 kpc from exciting stars Slide

$\to \left\langle \frac{d\eta}{df} \right\rangle$ 4.3 to 7×10^{-41} W.m^{-3}. ster^{-1} Hz^{-1} at 10 MHz.

Now recall $\langle \frac{d\eta}{df} \rangle \propto a(\gamma)\, B_\perp^{\gamma+1/2}\, K\, f^{-(\gamma-1)/2}$

Measurement of $\langle \frac{d\eta}{df} \rangle \rightarrow \langle K B_\perp^{\gamma+1/2} \rangle$ along line of sight.

Take K from cosmic ray data at 4.5 GeV (virtually unmodulated) - it is uncertain at higher E due to small no. of electrons detected, and γ from radio data

$\rightarrow \langle B_\perp \rangle \sim (6 \pm 2) \times 10^{-6}$ gauss.

For this line of sight, if assume that emissivity is entirely contributed by spiral arms, $\langle \frac{d\eta}{df} \rangle_{arm} \sim 2 \times 10^{-40}\ \mathrm{W\ m^{-3}\ ster^{-1}\ Hz^{-1}}$

$\rightarrow \langle B_\perp \rangle_{arm} \sim (1.6 \pm 0.5) \times 10^{-5}$ gauss for same K.

Comments

① $\langle B_\perp \rangle$ consistent with that estimated from shape of spectrum (matching $\beta(f)$ to $\gamma(E)$)

② $\langle B_\perp \rangle$ more typically about 1 to 3×10^{-6} gauss from $B_\parallel$ measured in Zeeman effect experiments in this direction.

③ For the future, higher resolving powers → more regions, smaller correction for T_{BG} spillover, may be able to determine distribution of $\langle \frac{d\eta}{df} \rangle$.

Similar technique can be applied to determine extragalactic background. Look at absorption in an extragalactic HII region. Only the isotropic component is left.

Reber 2.1 MHz map. 7° beam.

Also shows absorption at $b=0$. Slide

LMC fills beam. At 2.1 MHz, $\tau = 1$ for $E \sim 6\ \mathrm{cm^{-6}\ pc}$.

In fact, very little absorption in LMC, ~ 5× less than by extrapolation of Bride model.

Possibilities

① Interstellar absorption so great that LMC is "over the horizon" — not likely.

②. LMC contains <u>very</u> little HII → not likely from HF radio continuum maps

③. Extragalactic background cuts off.
Typical radio source spectrum is still going up at 10 MHz, although most IPS sources have cut off or fallen. But SSA could set in between 10 and 2 MHz. Or, possibly, intergalactic absorption; here anyone's guess is good.

Satellite studies.

By and large have confirmed the above.

RAE-1. Launched July 4 1968. <u>Slides.</u>

6000 km altitude circular orbit ($\varepsilon = 0.002$)

Two 229-m V antennas made of 1.3 cm diam hollow booms deployed after launch. Major problem is thermal deformation across boom cross-section when only one side illuminated by $\odot$. Booms are perforated, silver-coated outside and black-coated inside.

Satellite stabilised by gravity-gradient forces so that one V is <u>down</u>, other <u>up</u>. TV camera monitors shape of antennas by looking at tips of V's. Maximum excursions < 15 metres, oscillations < ±3°.

Lower V for interference monitor
Upper V for radio astronomy.

Record 0.4 to 9.2 MHz. 37-m dipole for < 1 MHz, electrically short
~100° beam

13°×27° at 9.2 MHz.

All-sky average spectrum shows max. near 3MHz due to interstellar diffuse HII.

Northern sky disc → cut-off appropriate to free-free absorption uniformly mixed with emission of $\beta = 2.4 \pm .05$ — good confirmation of the ground-based spectrum.

Slide

North halo minimum shows a superimposed component least-squares fitted by RAE workers on assumption that it lies entirely beyond disk.

→ Isotropic spectrum with cut-off down ~ ×5 at 2 MHz, in good agreement with interpretation of Reber's map.

Slide

Clark, T.A., Brown, L.W. & Alexander, J.K. *Nature*, in press.

Dilute interstellar electron gas

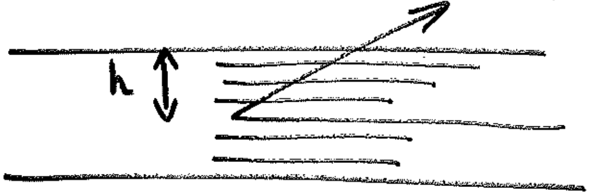
Bridle & Venugopal, *Nature*, 224, 545 (1969).

All low-b radio sources show spectral flattening below ~ 25 MHz, except for a handful of unidentified sources which might be local.

Enables investigation of interstellar electron gas. For sources with HF power laws and non-compact structure, predict S(10).

$$\frac{S(10)\ \text{obs}}{S(10)\ \text{pred}} \sim e^{-\tau(10)} \quad \text{where } \tau = \int_0^L \kappa \, dl \ \text{along line of sight.}$$

Suppose dilute electron gas stratified // to b=0°.



Path length at height z above plane is $\Delta z \operatorname{cosec} b$

$$\tau = \int k(z) \operatorname{cosec} b \, dz \ \text{through plane}$$

So for extragalactic sources, outside disc τ should be $\propto \operatorname{cosec} b$

Extrapolate to b=90°, → $\tau(10)$ at pole, $= \int_0^h k(z).\,dz$.

$=$ [redacted] $\langle k \rangle h$.

Find that $\tau(10)$ at pole $= 0{\cdot}10 \pm 0.02$

Look at galactic sources, $\tau = \int_0^L k\,dl$

Known L, $\langle k \rangle \sim \langle \frac{\tau}{L} \rangle$

$\sim 0{\cdot}34 \pm .10$ kpc^{-1}.

Hence scale height $h \gtrsim 350$ [redacted] pc.

Much thicker than HI disc (100pc), comparable to thickness of synchrotron emission disc deduced by Baldwin from distribution of nonthermal emission. Ionized gas has same scale height as magnetic field?

Now $\langle k \rangle \propto \langle n_e^2 T_k^{-3/2} \rangle$ in dilute gas.

B&V. from pulsar statistics and considerations of statistics of $R = \frac{DM}{HM}$

$\rightarrow \langle n_e \rangle \sim 0.02\ \mathrm{cm}^{-3}$ between HII regions.

Clumpiness ξ, $\langle n_e^2 \rangle = \frac{\langle n_e \rangle^2}{\xi}$

$\xi = 0.1$ gives $\langle T_k \rangle \sim 1000$ K.

$\langle \frac{n_e}{n_H} \rangle \sim .02$

} Consistent with low-energy c.r. or soft X ray heating of interstellar gas. Not readily consistent with UV heating.

Free-free emission from this medium at high f (cm wavelengths) would be expected to have much smaller emissivity than the nonthermal emission, allowing plausible extrapolation of the nonthermal spectrum. Hence the ~11cm bgrd from between HII regions should be predominantly nonthermal. Was once (Westerhout 1958) thought not to be so, but now (Altenhoff 1968) probably so.

Note that this work refers mostly to $70 < l < 220$.

CR ⟺ Radio.	Webber, W.R., Aust. J.P., 21, 845 (1968)
Galactic Spectrum	Bridle, A.H., M.N. 136, 219 (1967)
Extragalactic bgnd.	as above, both Bridle, A.H., Nature, 219, 1136 (1968) Clark, T.A., Brown, L.W. & Alexander, J.K., Nature, in press.
Magnetic field	Okuda & Tanaka, B.A.N., 20, 129 (1968) Webber, as above Bridle, A.H., M.N., 138, 251 (1968)
Interstellar HII	Bridle & Venugopal, Nature, 224, 545 (1969)
LF.	Reber, J.F.I., 285, 1 (1968) Alexander, J.K., Brown, L.W., Clark, T.A. & Stone, R.G., Astron. Astrophys. (1970)