The Sky at Very Low Frequencies

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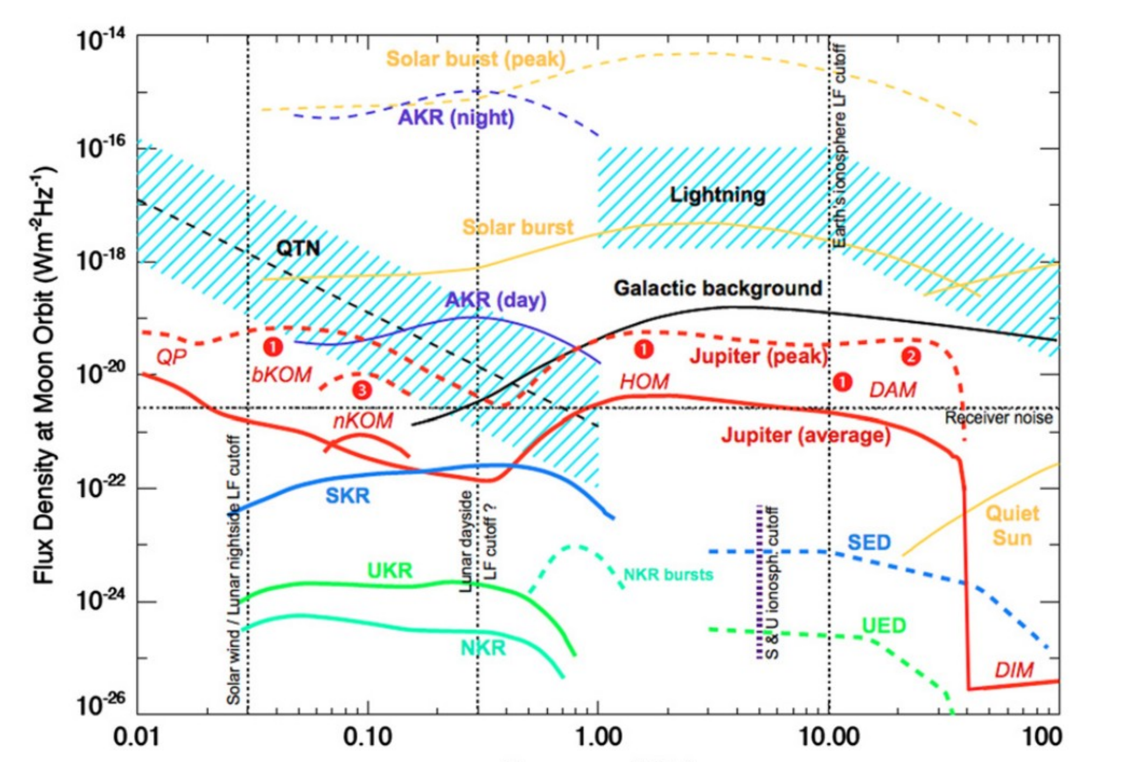
Overview

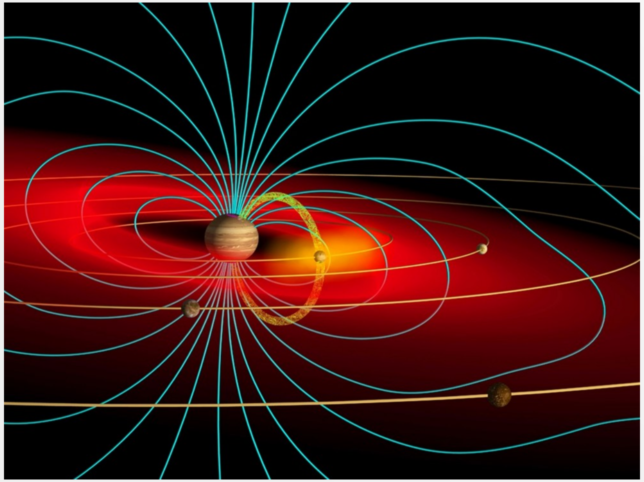
- Sources
  - Solar System
  - Galactic
  - Extra-galactic
- Propagation
  - Plasma scattering
  - Free-free absorption
- Observations
  - From Earth
  - From Space
  - Indirect

Sources — Solar System

- bKOM, HOM, DAM all via the Electron Cyclotron Maser (ECM) mechanism.
- nKOM from Io's plasma torus.
- Decametric radiation from electrostatic discharge (ED, lighting) and Jupiter's interaction with Io.
- QTN = Quasi thermal noise

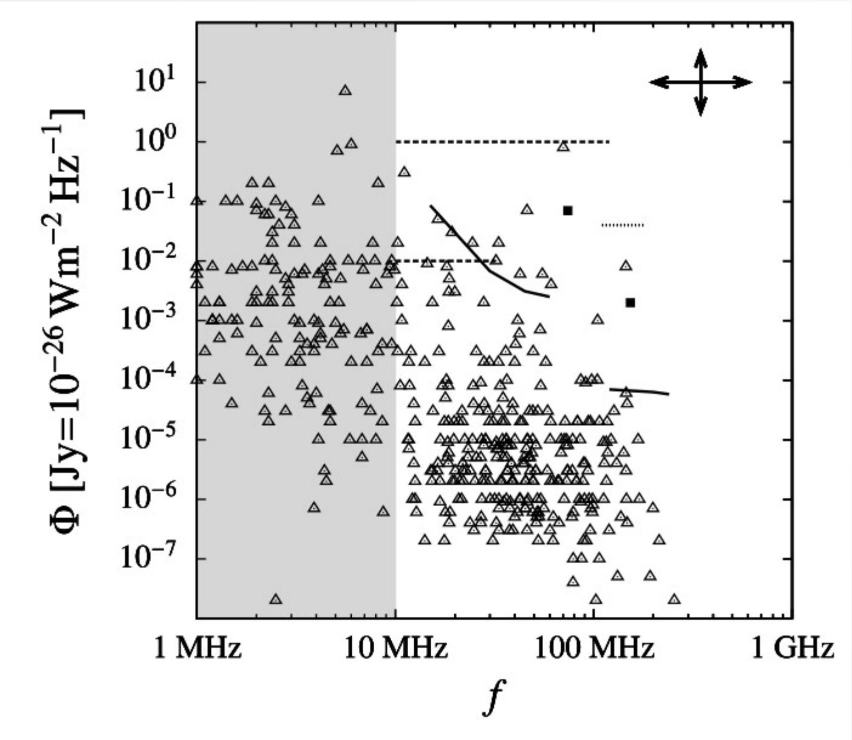


Zarka et al., (2012)


John Spencer via astronomy.com

Hectometer (HOM), Decameter (DAM), broad/narrowband kilometer (b/nKOM). Decimeter (DIM), electrostatic discharge (ED)

Sources – Exoplanetary?

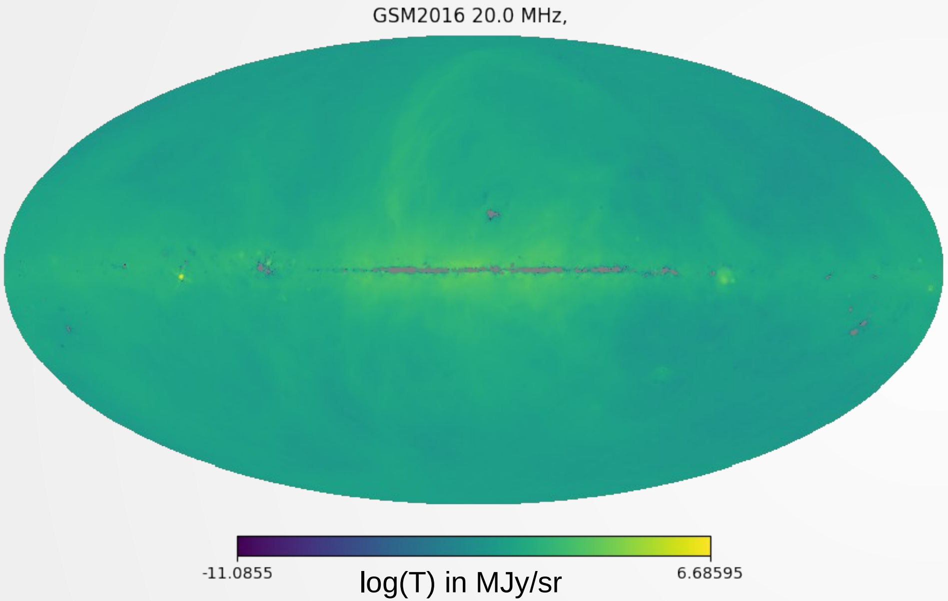


Predicted fluxes and spectral peaks of radio emissions from known exoplanets, assuming a rotation-dependent planetary magnetic field.
From: Grießmeister et al. (2011)

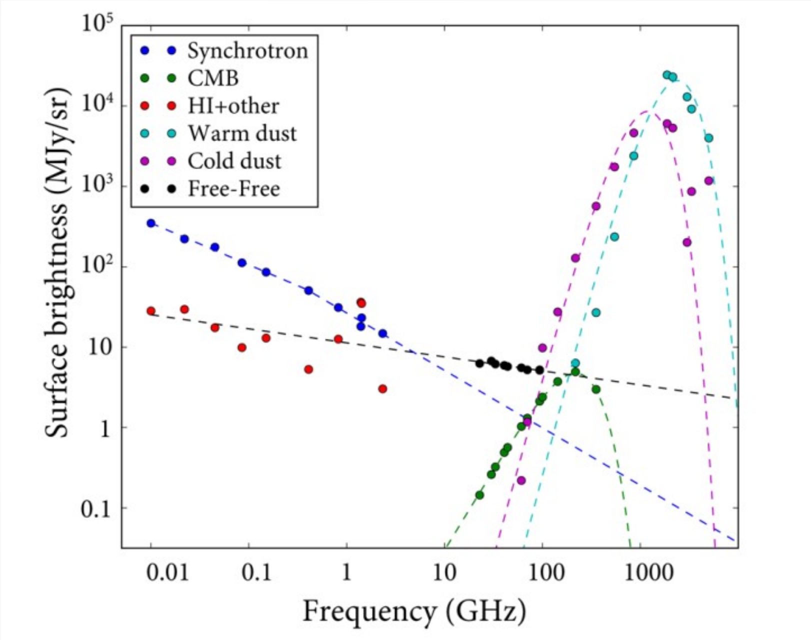
Image: Chuck Carter/Caltech/KISS
https://royalsocietypublishing.org/doi/full/10.1098/rsta.2019.0564

- Hot Jupiters with strong magnetic fields interacting with host stars the way Io interacts with Jupiter.
- Predicted emission fluxes are below typical observing thresholds at higher frequencies
- Below the ionosphere cutoff, potentially much brighter.

Sources — Galactic



The Global Sky Model, extrapolated from the Haslam (1982) map [Zheng et al. (2016)]

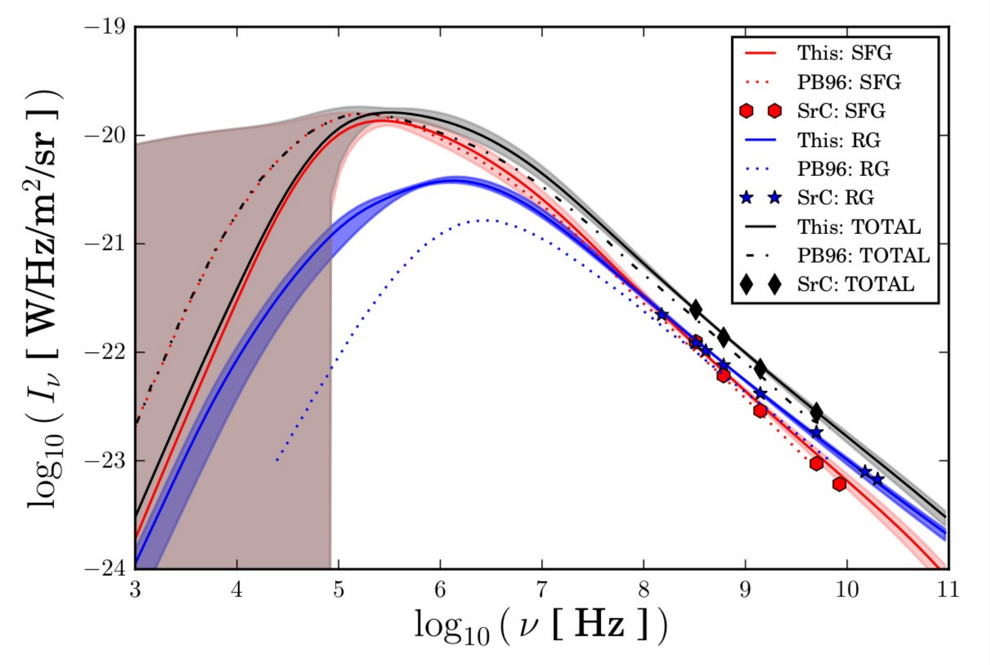


Components fitted in the Global Sky Model (GSM) Zheng et al. (2016)

- Galactic synchrotron emission
  - Relativistic electrons spiral around B-fields.
  - $T_b \propto \nu^{-2.5}$

Sources – Extragalactic

- Cosmic Radio Background
  - Synchrotron emission
  - Free-free emission
- Spectra differ between radio galaxies and star-forming galaxies.
- Estimates made by combining models of galaxy evolution with models of galaxy spectra.



Niţu et al. (2021) theoretical estimates of cosmic radio background from star forming galaxies (SFG) and radio galaxies (RG), compared with Protheroe & Biermann (1996) and with observed source counts.

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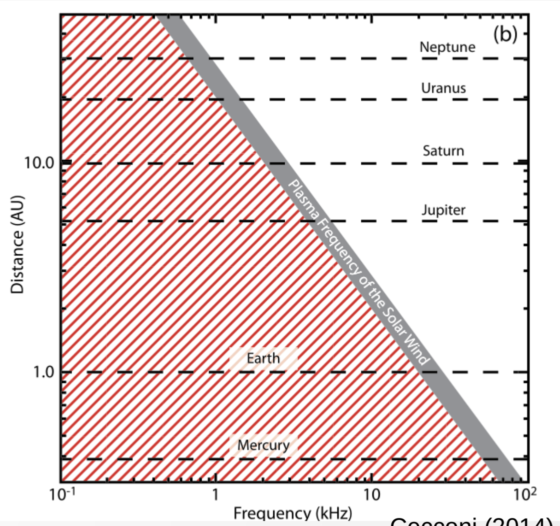
Propagation



Cecconi (2014)

- Opacity due to plasma frequency $\nu_p = \frac{e}{2\pi}\sqrt{\frac{n_e}{\epsilon_0 m_e}} \sim 9\sqrt{n_e}\ \ \mathrm{Hz}$
  - Ionosphere: ν_p ~ 10 MHz
  - Solar Wind: ν_p ~ 24 kHz (at 1 AU) → 2.34 kHz (@ 10 AU)
  - ISM: ν_p ~ 30 kHz
  - IGM: ν_p ~ 4.5 δ_e $(1 + z)^{3/2}$ Hz ≈ 0.2 Hz (at z=0) [Lacki (2010)]
- Thermal bremsstrahlung from ionized hydrogen (free-free absorption)
  - Dominant at low frequencies.

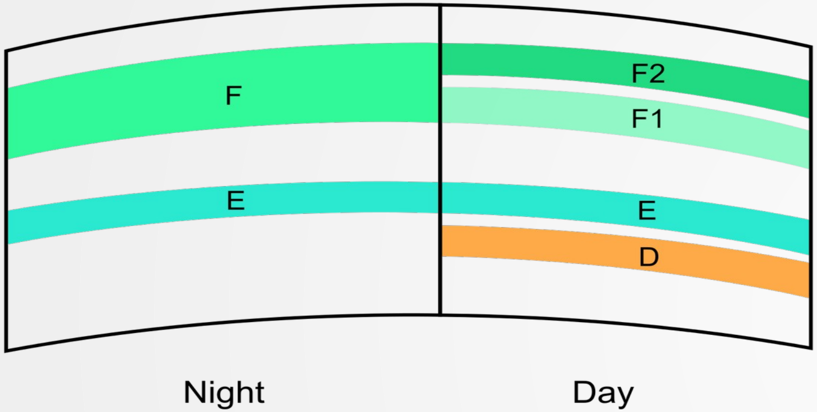
$$\tau \approx 3.28 \times 10^{-7} \left(\frac{T}{10^4\mathrm{K}}\right)^{-1.35} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1} \left(\frac{\mathrm{EM}}{\mathrm{pc\ cm^{-6}}}\right)$$

where $\mathrm{EM} = \int n_e^2 ds$

Emission measure

  - The warm ionized medium (WIM) of the Galaxy becomes a significant barrier.
- Faraday Rotation
  - Linear polarization angle rotates by $\Delta\psi = \mathrm{RM}\,\lambda$ for $\mathrm{RM} = \int n_e B_{||} dl$
  - RM ~ 100 rad / m^2 in the Galaxy.
  - Bandpass depolarization occurs over 2 kHz at 30 MHz [Erickson (2000)]

The Ionosphere



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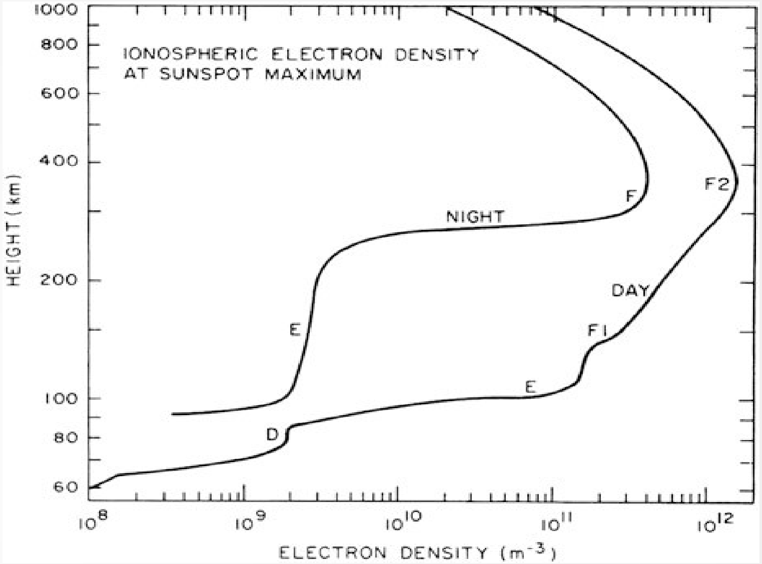
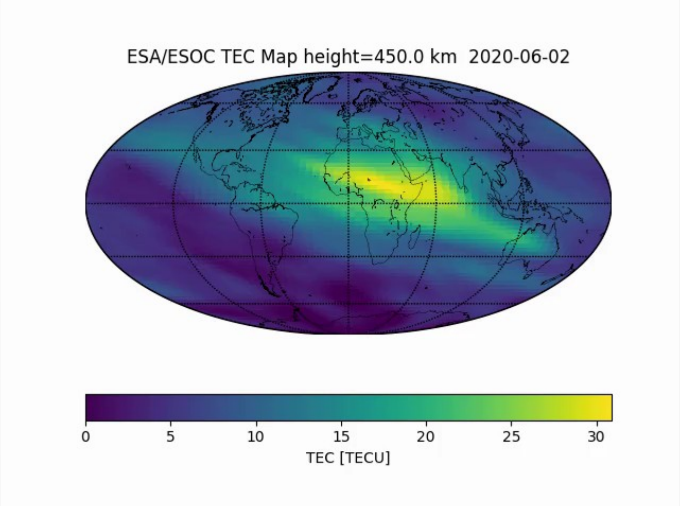
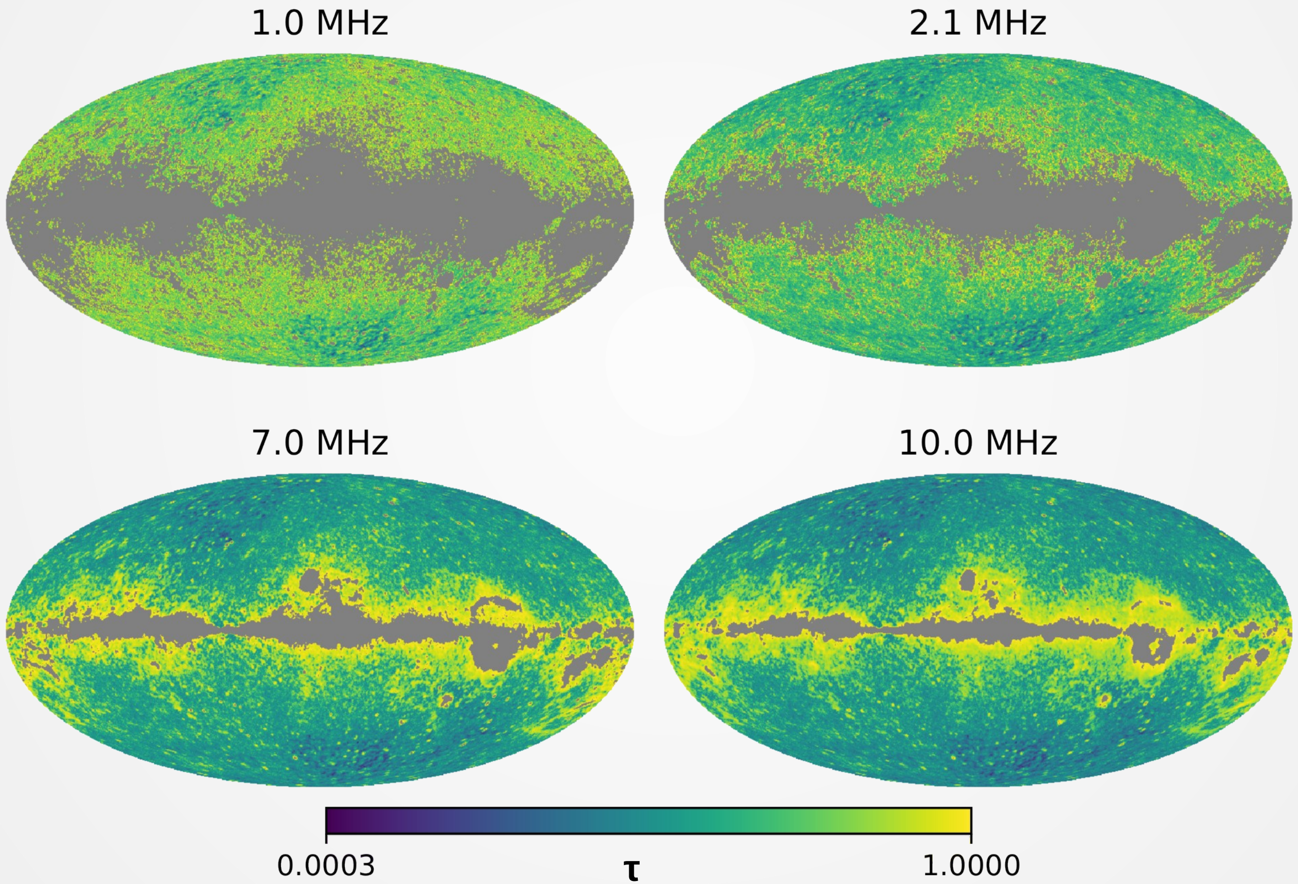


Thompson, Moran, & Swenson (2017), originally Evans & Hagfors (1968)



- Plasma in the upper atmosphere.
- X-ray, UV from the Sun, and cosmic rays ionize gas.
- Recombination at night.
- Strongly affected by solar activity.
- Strongest near the equator and at day.

Free-Free opacity at low frequencies with Planck data.



Medians for τ < 1:

1.0 MHz: 0.19
2.1 MHz: 0.052
7.0 MHz: 0.0075
10.0 MHz: 0.0042

- Using EM and estimated electron temperature maps from the published Planck component maps (Planck Collaboration, 2015)
- Masked wherever τ > 1

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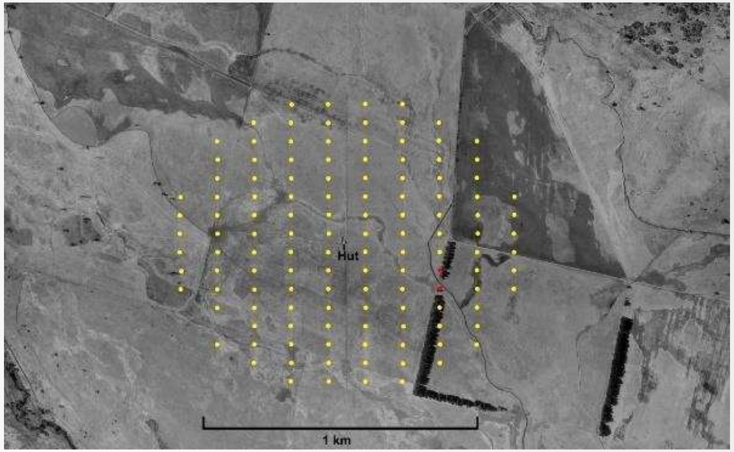
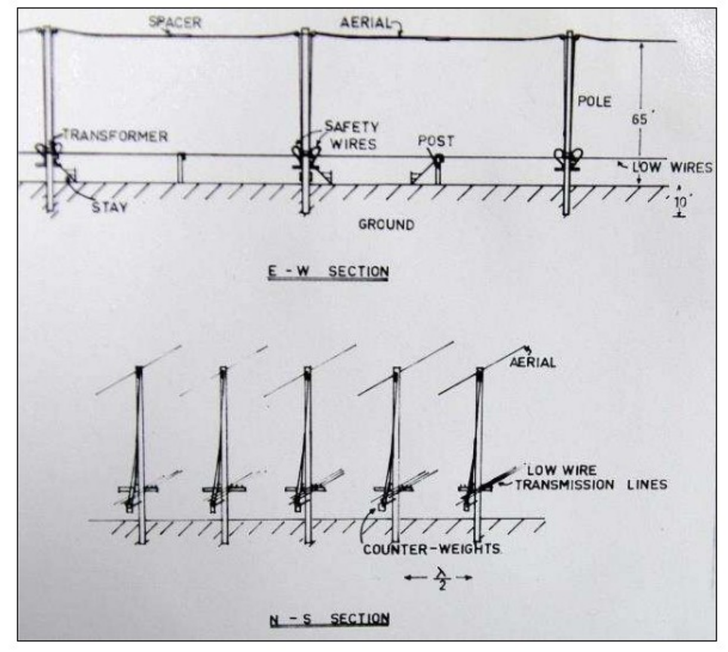
Observations

- Go to latitudes away from the equator where the ionosphere is weaker.
  - Pros: Can build larger arrays, get better resolution
  - Cons: Still under an ionosphere.
- Launch to space:
  - Pros: No ionosphere, and can use the Moon for radio shielding
  - Cons: Exposure to terrestrial and planetary RFI, costly

Grote Reber's 2.085 MHz array

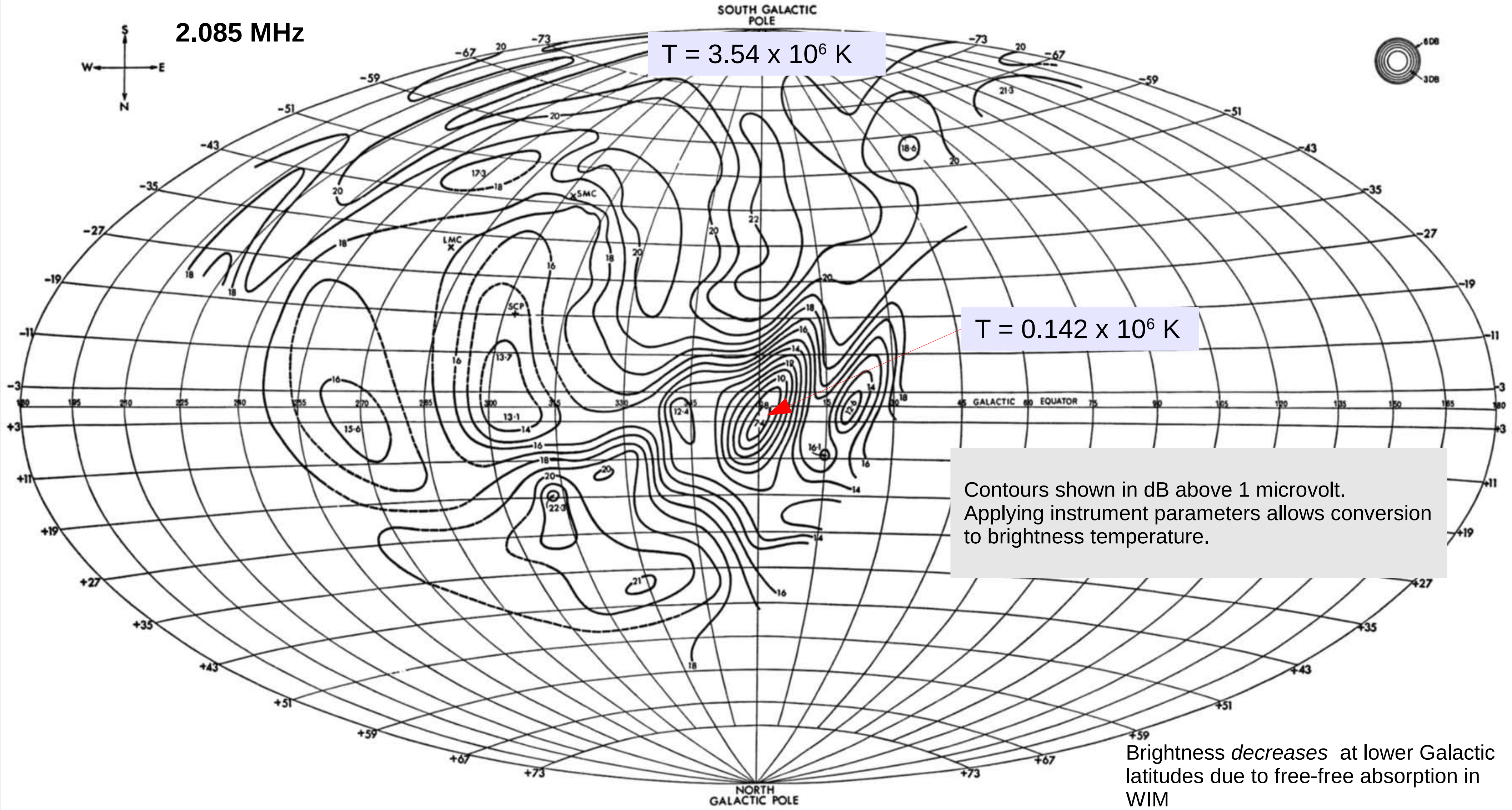
- Bothwell, Tasmania
- 128 poles, 134 m sep E-W sep, 67 m N-W sep.
  - Each pole carries a 1 λ dipole E-W
- Data collected from Feb 1963 to May 1967
- Beam area = 0.0121 steradian (FWHM ~ 6°)
- Antenna area = 0.905 km^2
- 0.3 s integration





Images from George, Orchiston, & Wielebinski (2017)

2.085 MHz



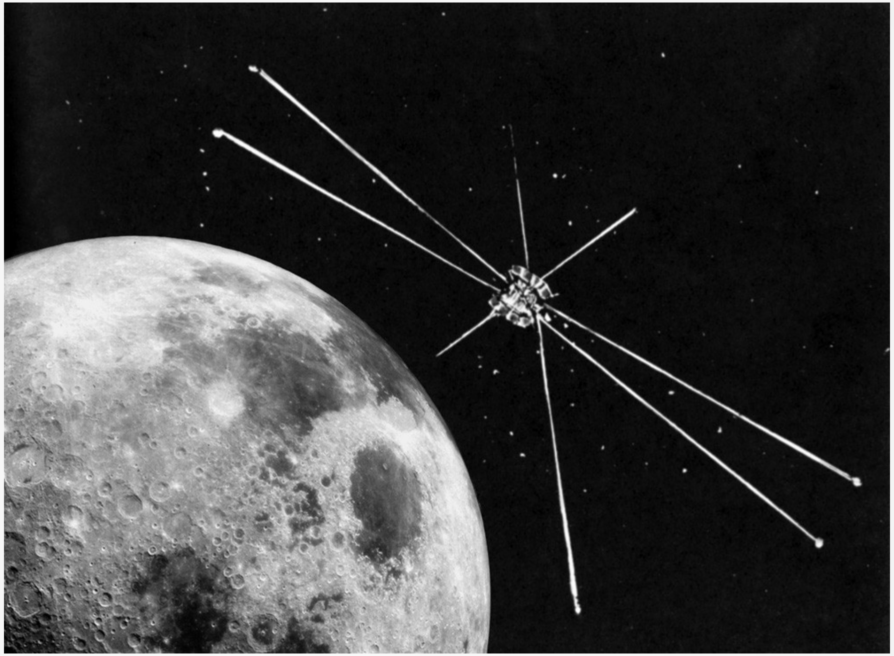
Contours shown in dB above 1 microvolt. Applying instrument parameters allows conversion to brightness temperature.

Brightness *decreases* at lower Galactic latitudes due to free-free absorption in WIM

Radio Astronomy Explorer 2

- Launched 10 June 1973
- Entered orbit 15 June 1973
  - 1100 km altitude
  - 59° inclination
- 25 kHz to 13.1 MHz
- Very wide beams:

Freq.	θ_E (FWHM)
9.18 MHz	37°
6.55	27
3.93	80
1.31	180
0.87	220



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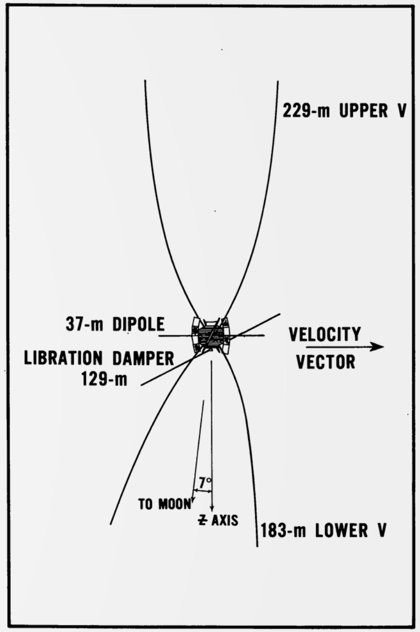
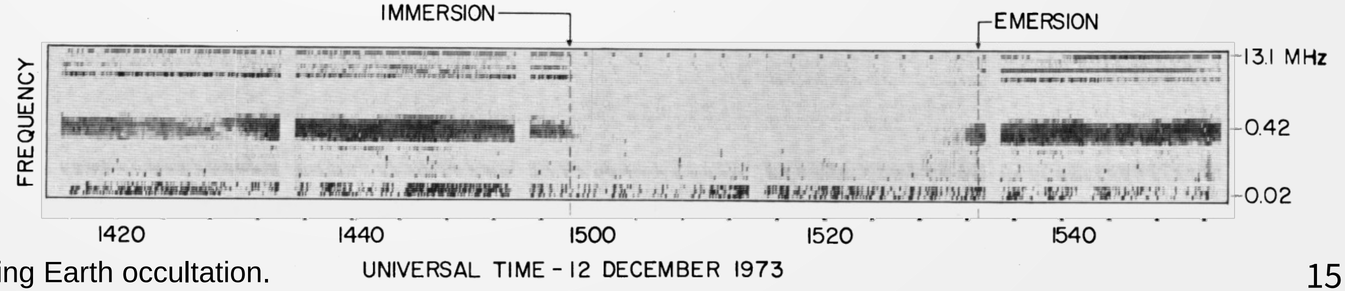
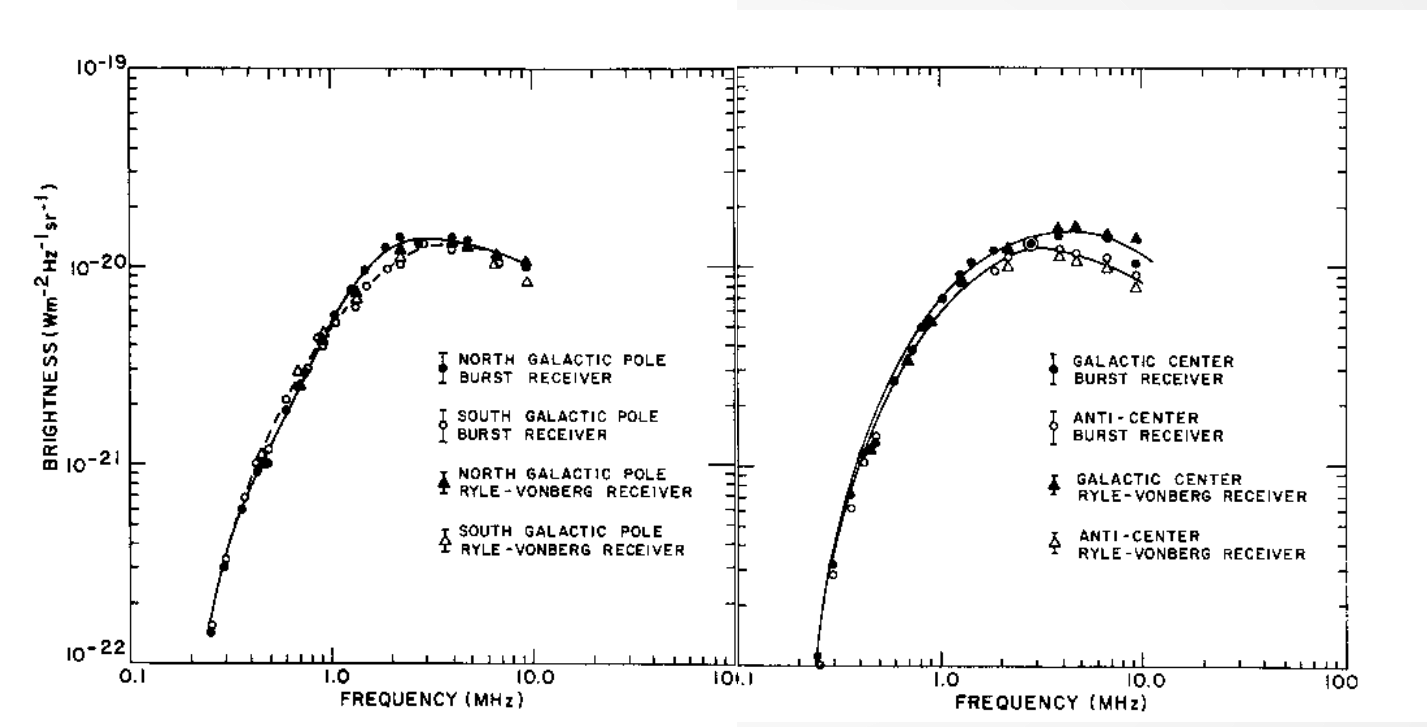


Alexander et al. (1975)



Spectrum during Earth occultation.
[Alexander et al. (1975)]

RAE-2

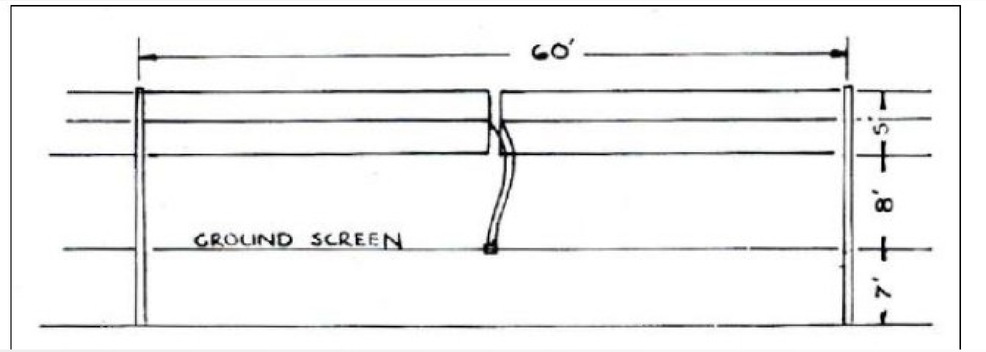


Novaco & Brown (1978)

- North and South Galactic poles
- Very little difference at high freq
  - F-F absorption path length extends beyond the Galaxy
  - Likely seeing Extragalactic contributions.
- Some deviation between 1 and 4 MHz

- Galactic center and anti-center
- Dominated by large structures toward Galactic center.
- Toward low frequencies, F-F absorption path length decreases
  - 10 to 50 pc at 0.3 MHz
- Short path length and wide beams = apparent isotropy

Hilary Cane – LLFA and DRAO



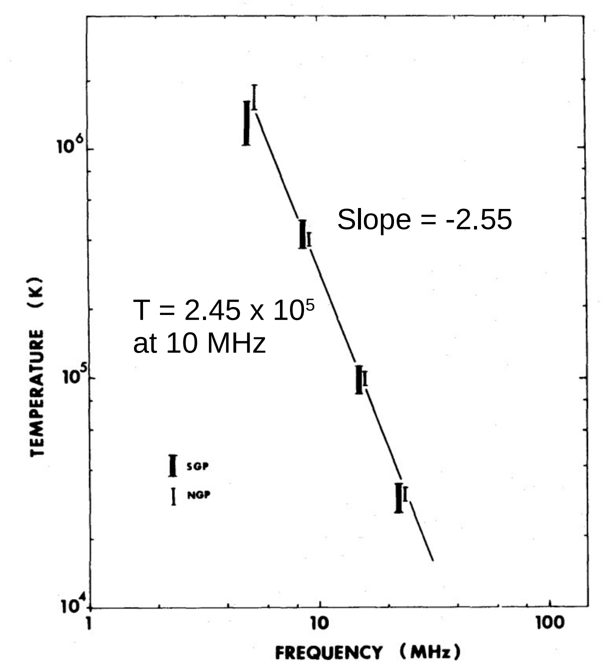
- Llanherne Low Frequency Array, Tasmania
- Approximately square, 64 rows of East-West dipoles
- 640 m x 640 m
- 0.5 λ dipoles, 1/8 λ over a ground screen.
- 2 — 18 MHz, beamwidth ~ 4.5° at 5.5 MHz
- Data collected from 1977 June to October in Tasmania
- Between midnight and dawn during winter months to minimize ionosphere losses

Images from George, Orchiston, & Wielebinski (2018)

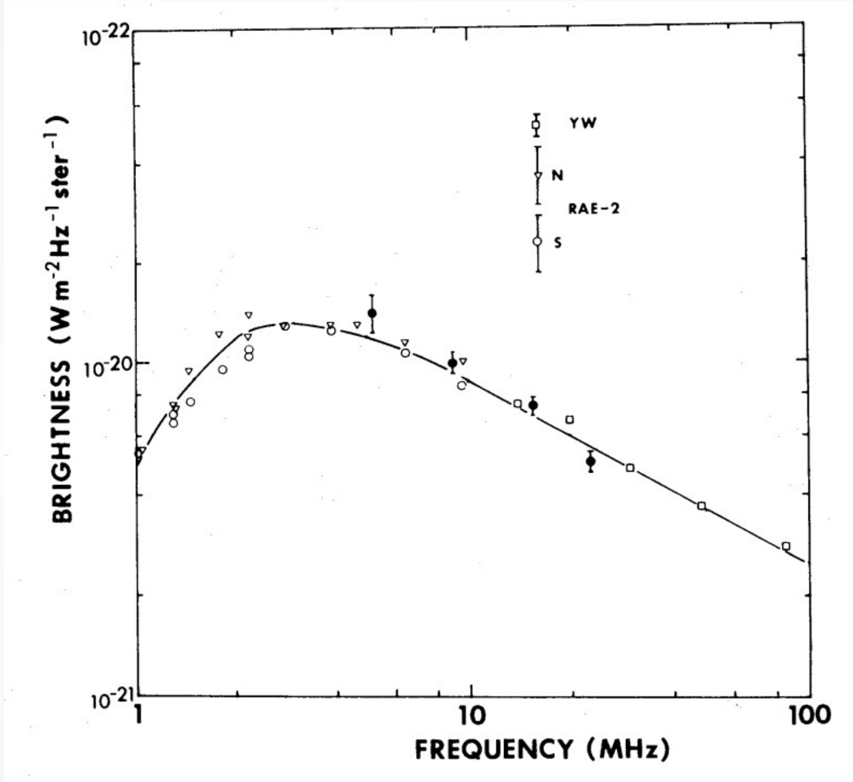
The equipment was later shipped to Penticton, BC, Canada to repeat observations in the Northern hemisphere.

Observations taken there from 1978 January to March

LLFA and DRAO observations

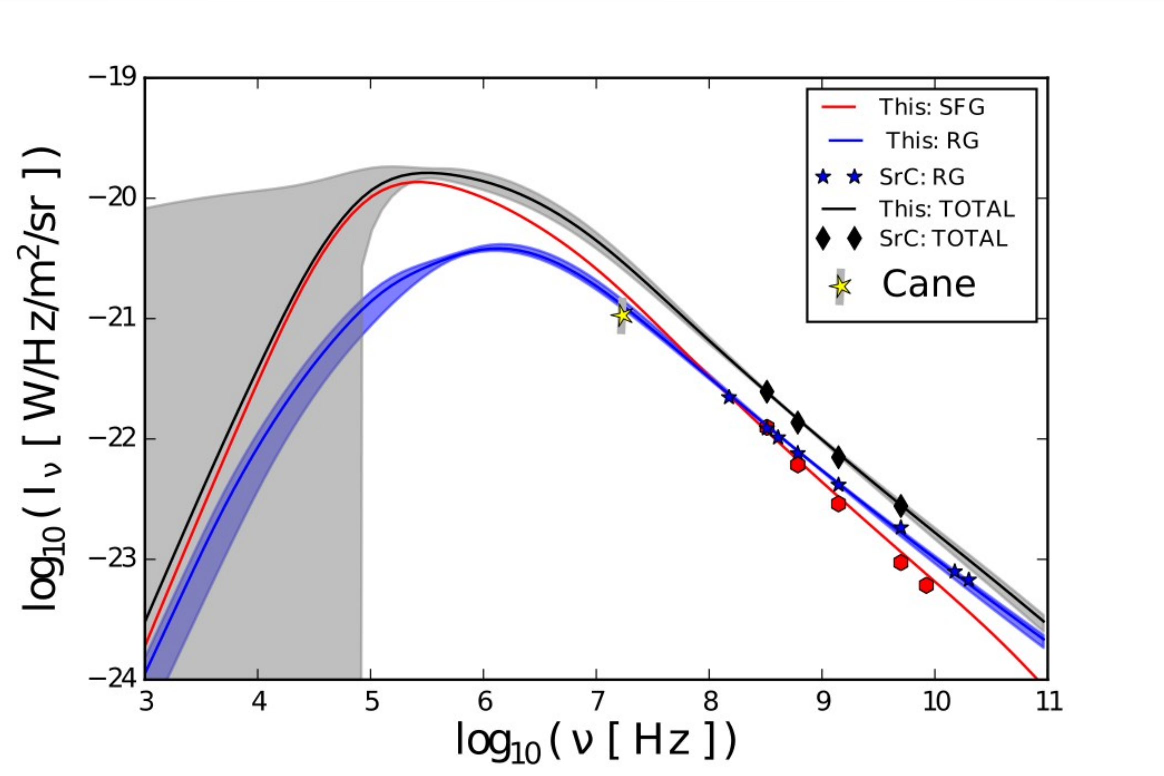


Cane (1979)



- 5.2, 9.0, 15.6, and 23.0 MHz
- Observations are compatible with results of RAE-2 and the higher frequency observations of Yates and Wielebinski (1966).
- Fit a two component model — Galactic and Extragalactic
  - Extragalactic component = $5.5 \pm 1.5 \times 10^4$ K at 10 MHz, consistent with higher-freq observations.
  - Assuming 500 pc scale height for MW disk (low, compared with more recent estimates from pulsar dispersion).

Comparison with Niţu et al. (2021)



- Adding Cane's extragalactic estimate to the Niţu et al. (2021) results
- Comparable to estimates with radio galaxies only, but not including SFG.

Wind/WAVES (1994)

- Launched 1 November, 1994 to L1
- Rotates every 3 s, antennae are in the spin plane (ecliptic)
- X -antenna: 2 x 50 m long, up to 1 MHz
- Y-antenna: 2 x 7.5 m long, 1 — 13.8 MHz
- Manning & Dulk (2001):
  - Observations from 6 May 1997

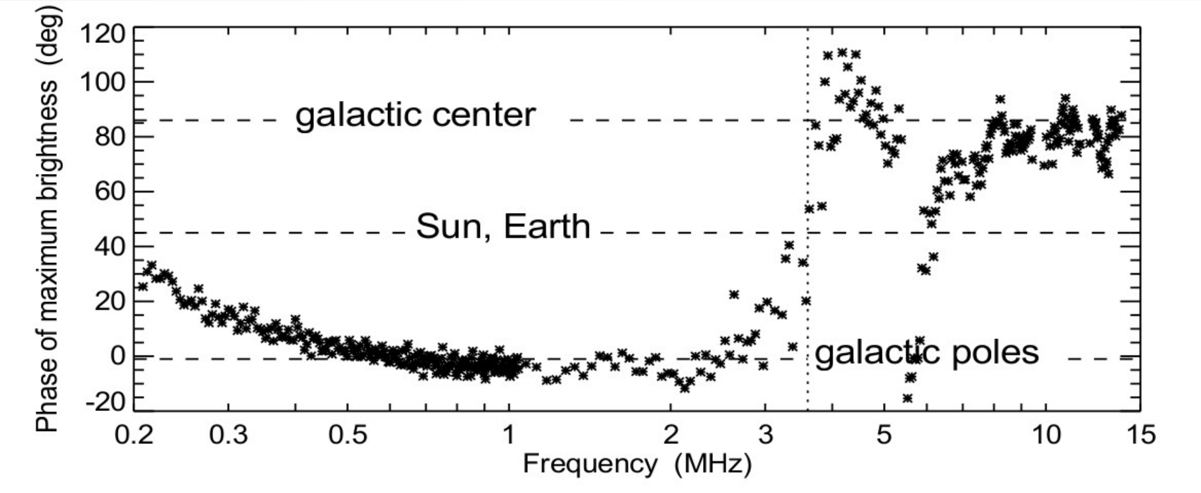
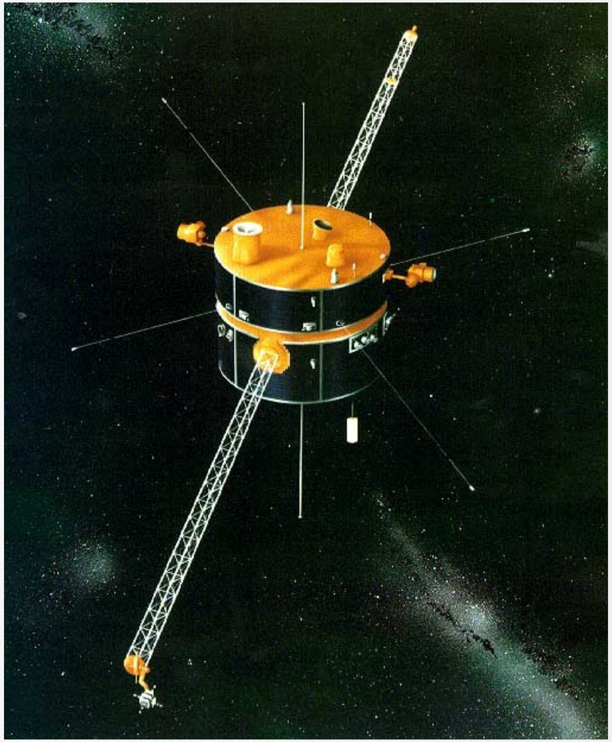


Fig 1. of Manning & Dulk (2001)



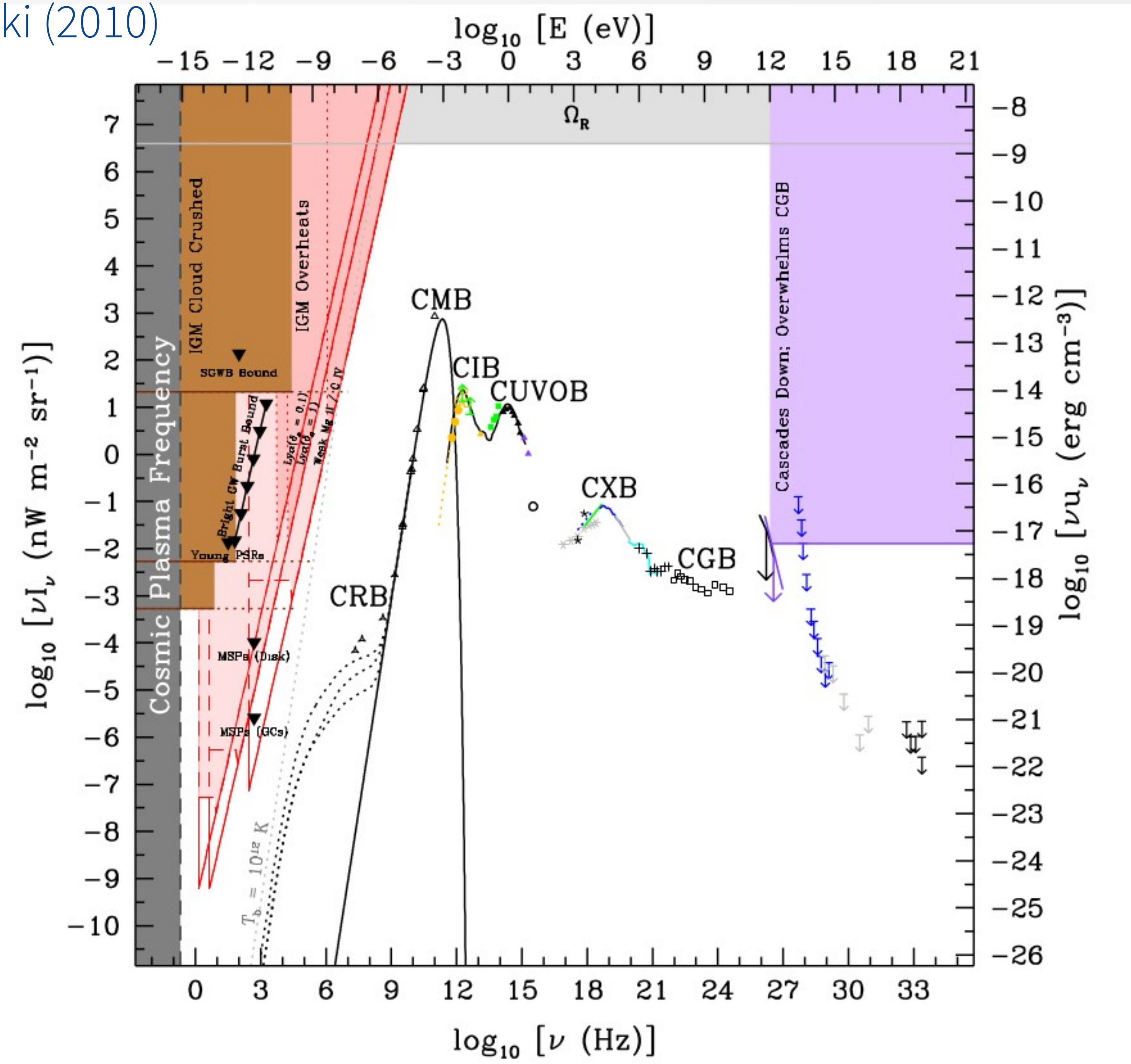
Wikimedia Commons, via NASA

Every half period (1.5 s), there is a roughly sinusoidal variation in intensity with amplitude given by maximum and minimum flux observed.

Phase of pattern gives direction of maximum brightness.

Indirect Inferences of Extragalactic — Lacki (2010)

- Constrain sub-MHz emission via other effects
- Radiation pressure can crush clouds in the IGM.
- Free-free absorption heats the IGM
- Cosmic rays in clusters should inverse-Compton scatter sub-MHz photons to higher frequencies.
- Synchrotron absorption heats the IGM.
- T = 10^{12} K line are shown as maximum synchrotron emission spectrum.
- Cosmic plasma frequency assuming δ_e ~ 0.002 provides strict lower bound at about 0.2 Hz.



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