Radioastronomy Science from the Moon

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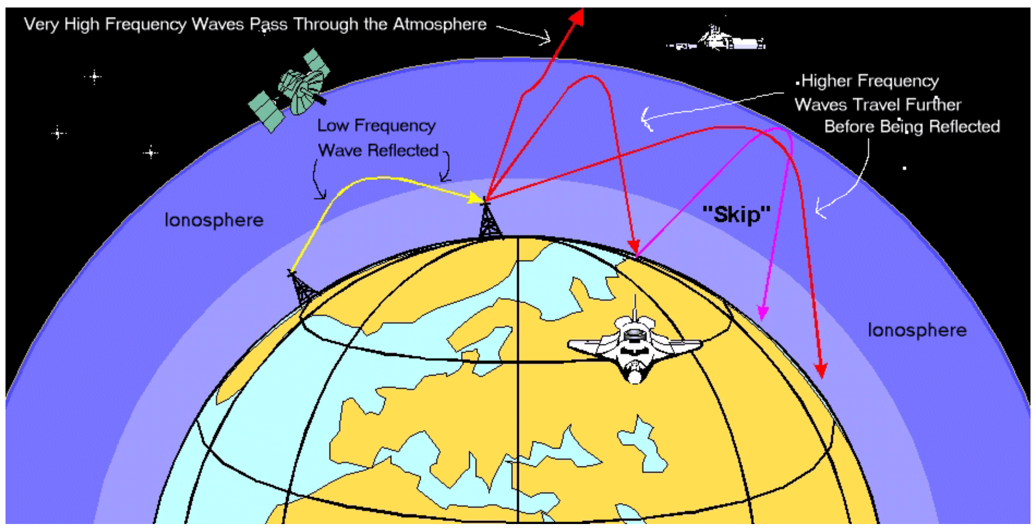
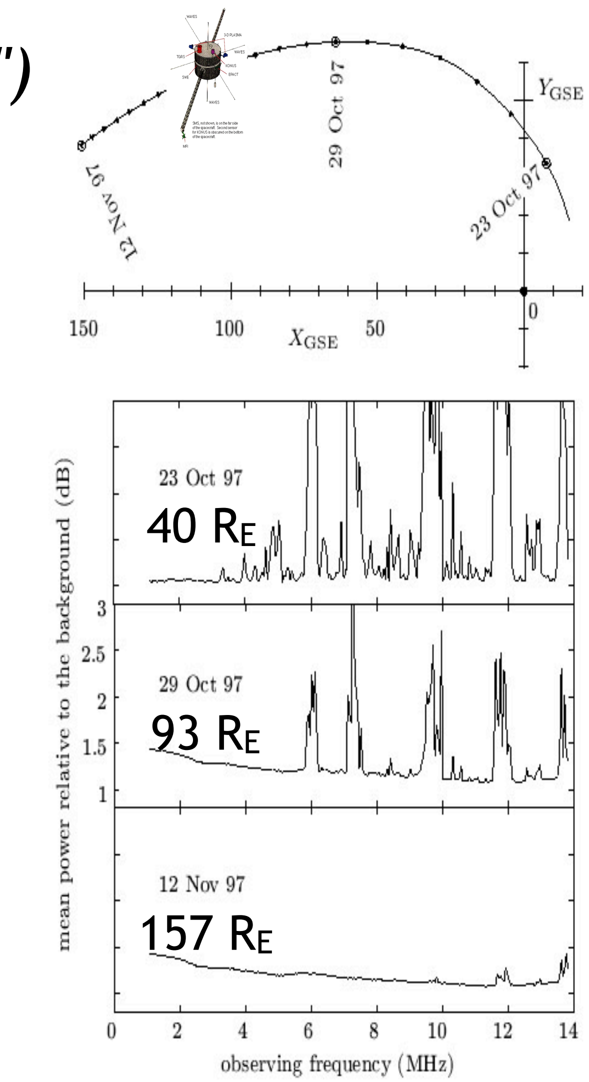
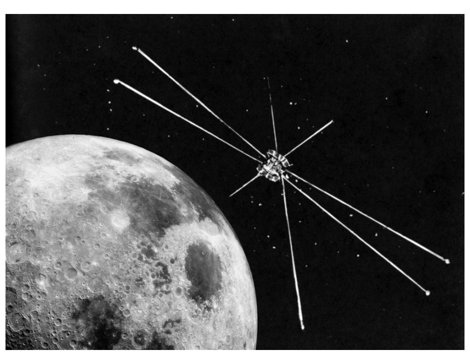
- Radioastronomy on the Moon is an Old idea. First proposals pre-date Apollo missions !
- The Moon (Far side especially) has been long recognized as unique astronomical platform, and a radio quiet zone by International Telecommunications Union
- No place on/near Earth is dark at Low Frequencies *(LF radio "smog")*

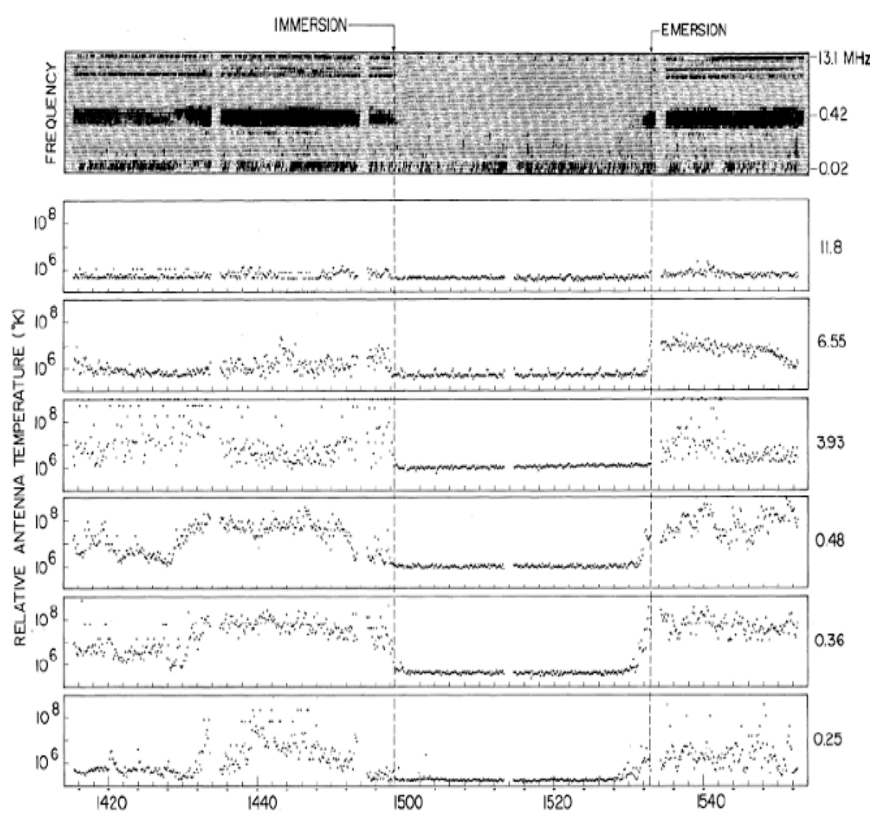




24h averages from Wind/WAVES

- RAE-2 : 1100 km circular orbit inclined by 59° / lunar equator

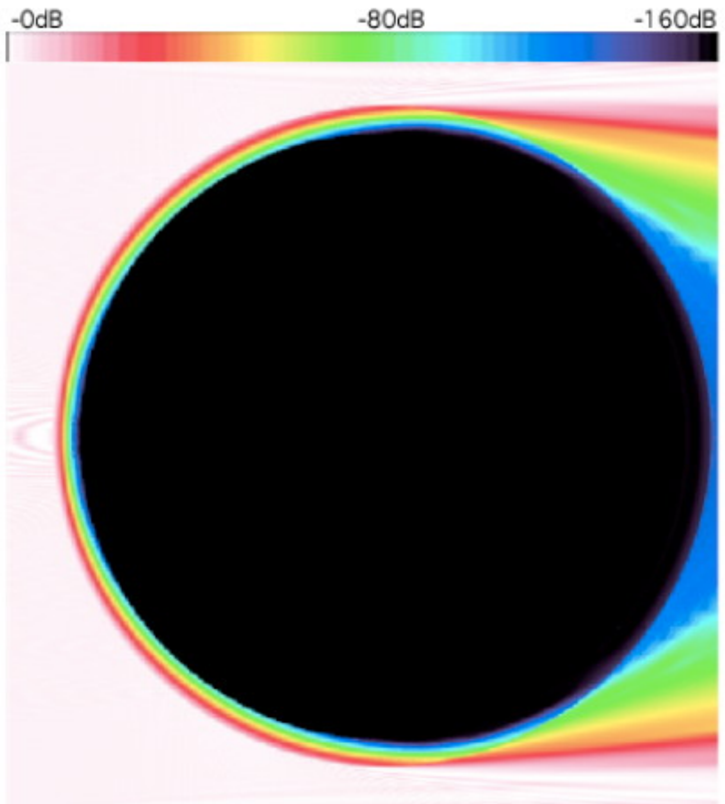




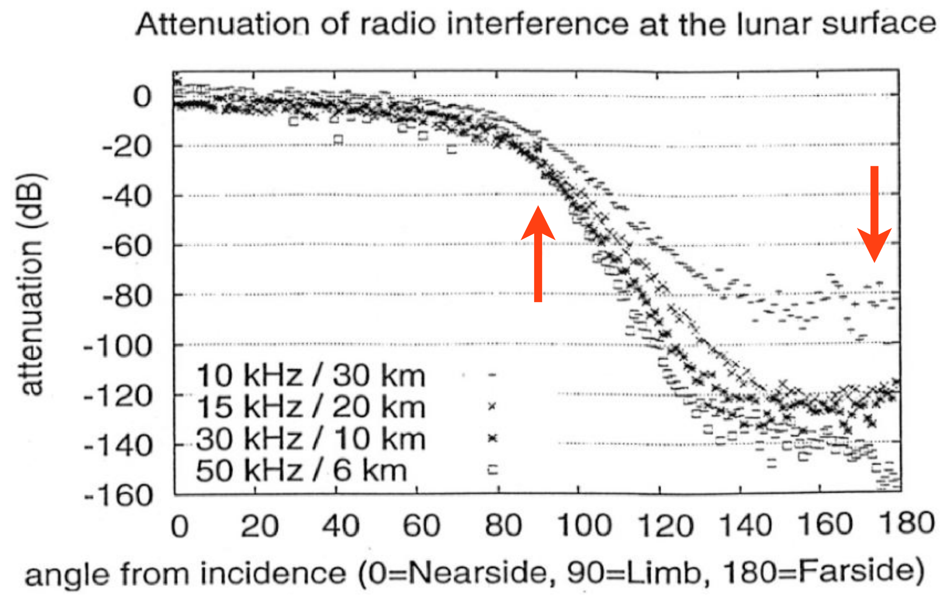
RAE-2 occultation of Earth (1973)

- Far-side of the Moon and eternally-dark craters at the lunar poles shielded from natural and man-made terrestrial RFI

→ AT NIGHT the most radio-quiet locations in the vicinity of the Earth.

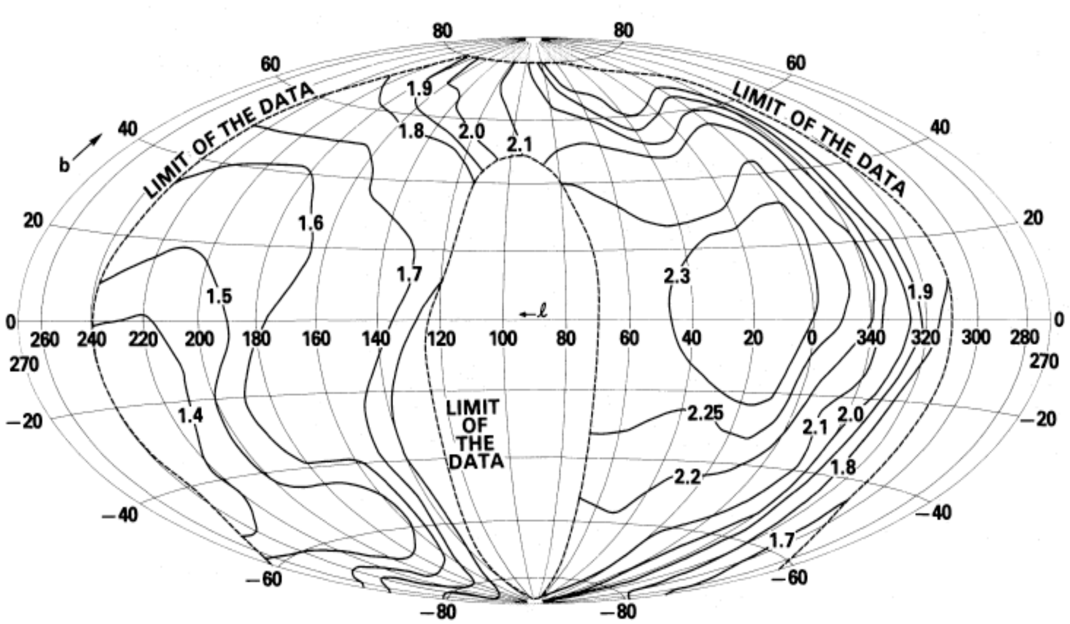


Attenuation of a 60 kHz radio wave due to propagation around the Moon with subsurface penetration and a lunar density model (Takahashi, 2003)



- Sensitivity limitation = *Background sky temperature always high (~10^{4-6} K)*

→ sensitivity can be increased by long integrations



CONTOURS ARE IN UNITS OF 10^6K

FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

T_{sky}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

RAE-2 observations (Novaco & Brown, 1978) : → no individual source identified

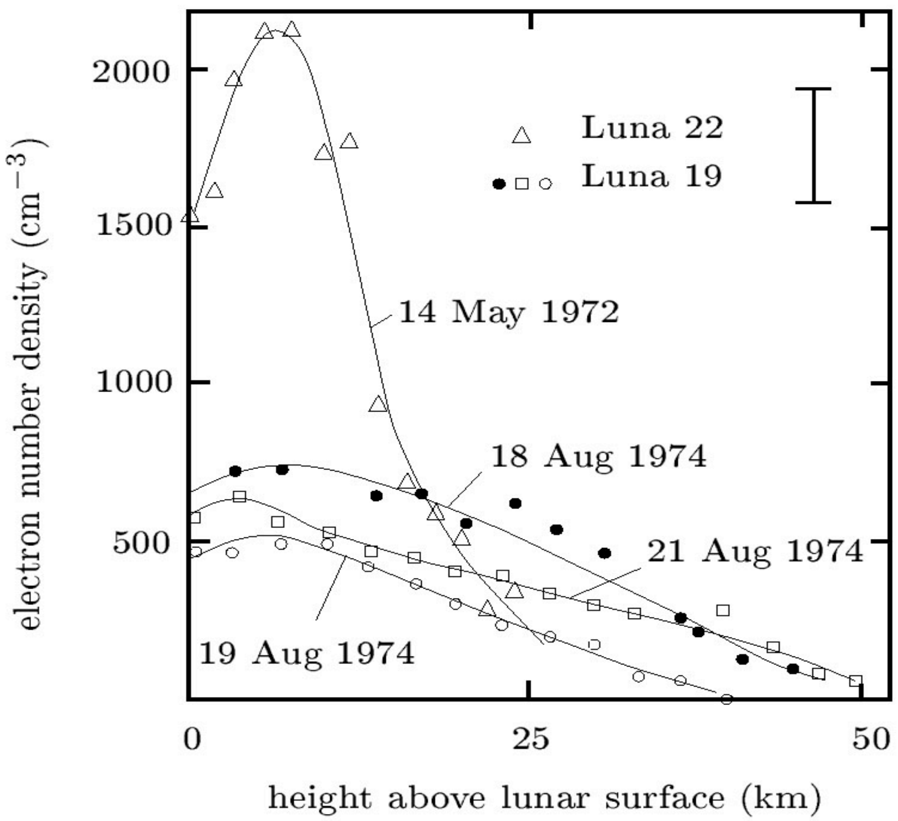
Galactic background flux density detected by a short dipole antenna :

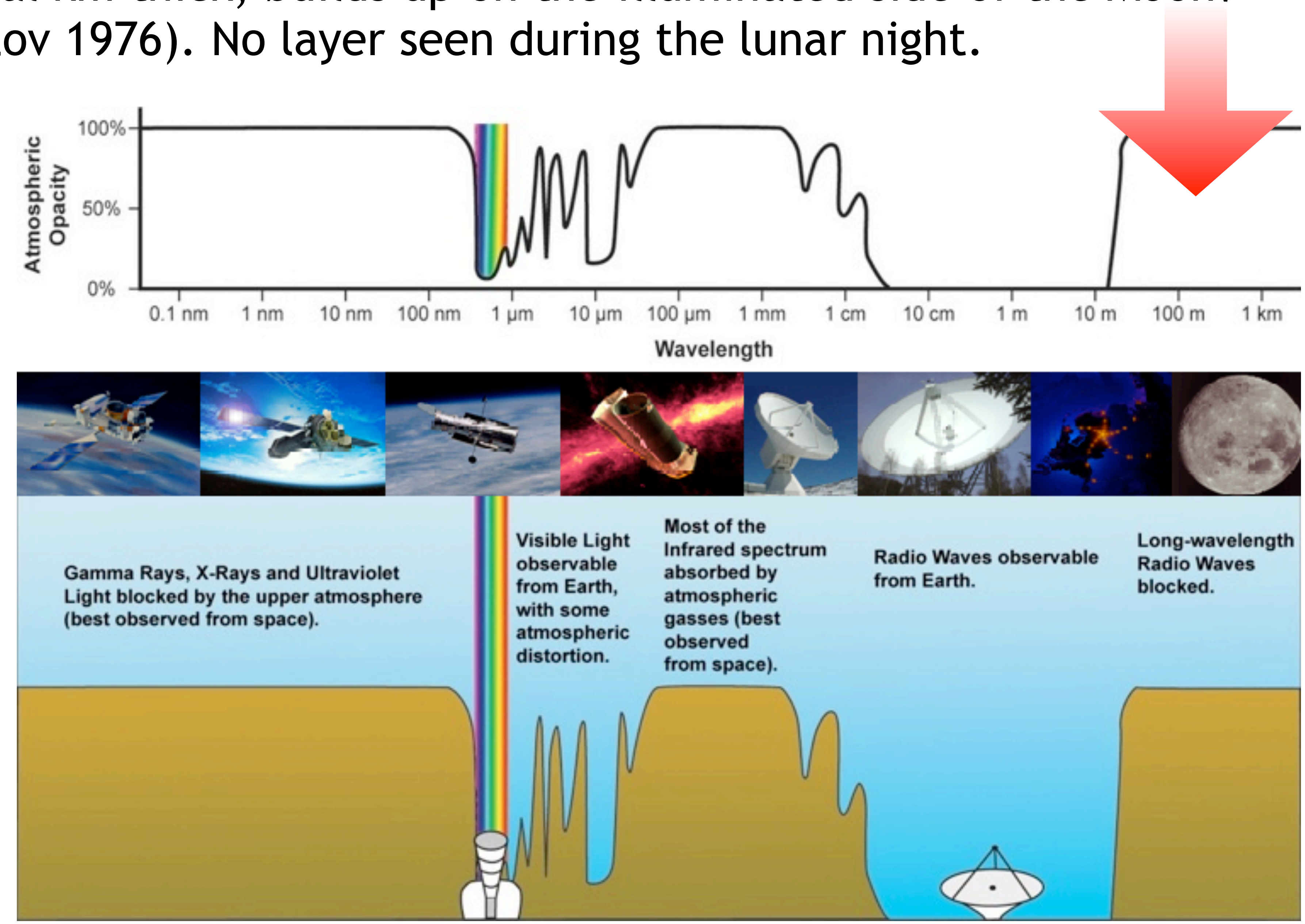
$S_{sky}{}^1$ ($Wm^{-2}Hz^{-1}$) = $2kT_{sky}/A_{eff} = 2kT_{sky}\lambda^2/\Omega$ with $\Omega = 8\pi/3$, $A_{eff} = 3\lambda^2/8\pi$

→ sensitivity with N dipoles, bandwidth b, integration time τ :

$S_{min} = S_{sky}{}^1/C$ with $C = N(b\tau)^{1/2}$

- Lunar ionosphere is very thin. Dual-frequency Luna spacecraft measurements suggest that an ionised layer, several km thick, builds up on the illuminated side of the Moon, with $f_{pe\text{-}max}$ ~0.5 MHz (Vyshlov 1976). No layer seen during the lunar night.





→ Lunar radio window down to a few 100s kHz or less, ~ unexplored.

- From Lunar Far Side or South Pole, it is possible with relatively simple instrumentation to make the first extensive radio astronomy measurements below 10-20 MHz.

① LF sky mapping + monitoring : radio galaxies, large scale structures (clusters with radio halos, cosmological filaments, …), including polarization, down to a few MHz

☺ Weak refraction/scintillation by ionosphere as compared to ground-based observations

☹ Interstellar and interplanetary media broaden sources to ~1" at 30 MHz, ~1° at 1 MHz

☹ Free-free absorption results in a foggy sky <1-2 MHz, but there are holes in the fog

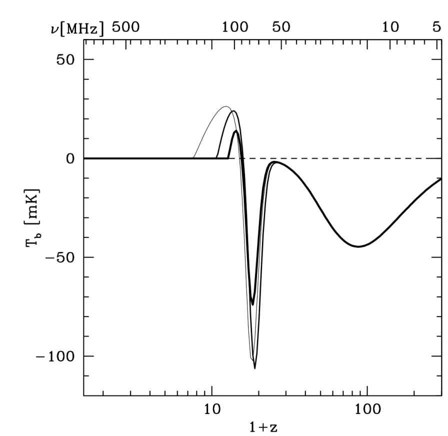
☹ Differential Faraday rotation limits polarisation studies

- Imaging capabilities best with a Space-Based Radio Array (e.g. SURO) or a Lunar radio array
- Precursor measurements 1-2 Landers (or 1 + Rover) : GonioPolarimetry + Global inversion of Interferometric Visibilities

② Cosmology : pathfinder measurements of the red-shifted H_I line that originates from before the formation of the first stars (dark ages, reionization)

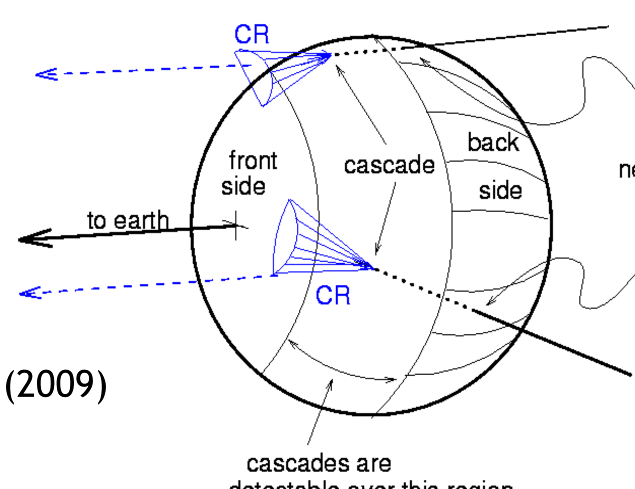
☹ Signal ~10^{-6} x galactic background → requires extreme quietness & long integrations

- Best with Large Radio Array, Far Side
- Precursor measurements possible from South pole : study foregrounds, set upper limits...



Pritchard & Loeb(2008)

③ Interaction of ultra-high energy cosmic rays and neutrinos with the lunar surface

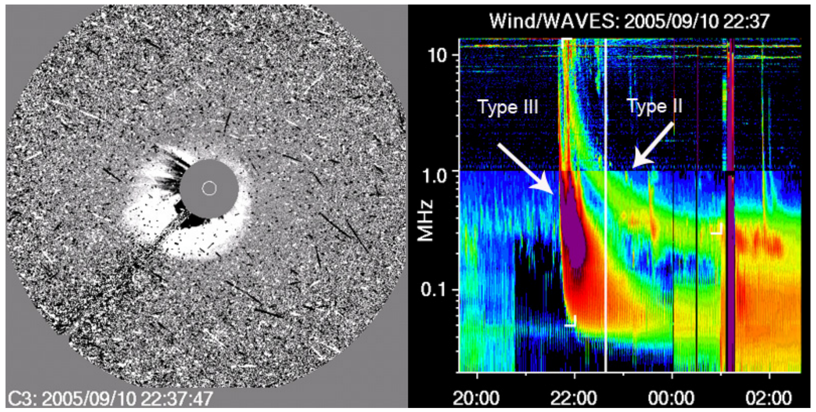


Jester & Falcke (2009)

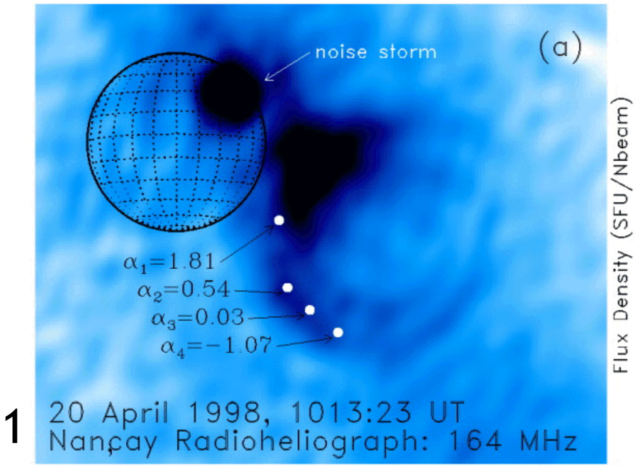
④ Low-frequency radio bursts from the Sun, from 1.5 Rs to ~1 AU : Type II & III, CME, ...

Space weather - Passive: through scintillation and Faraday rotation

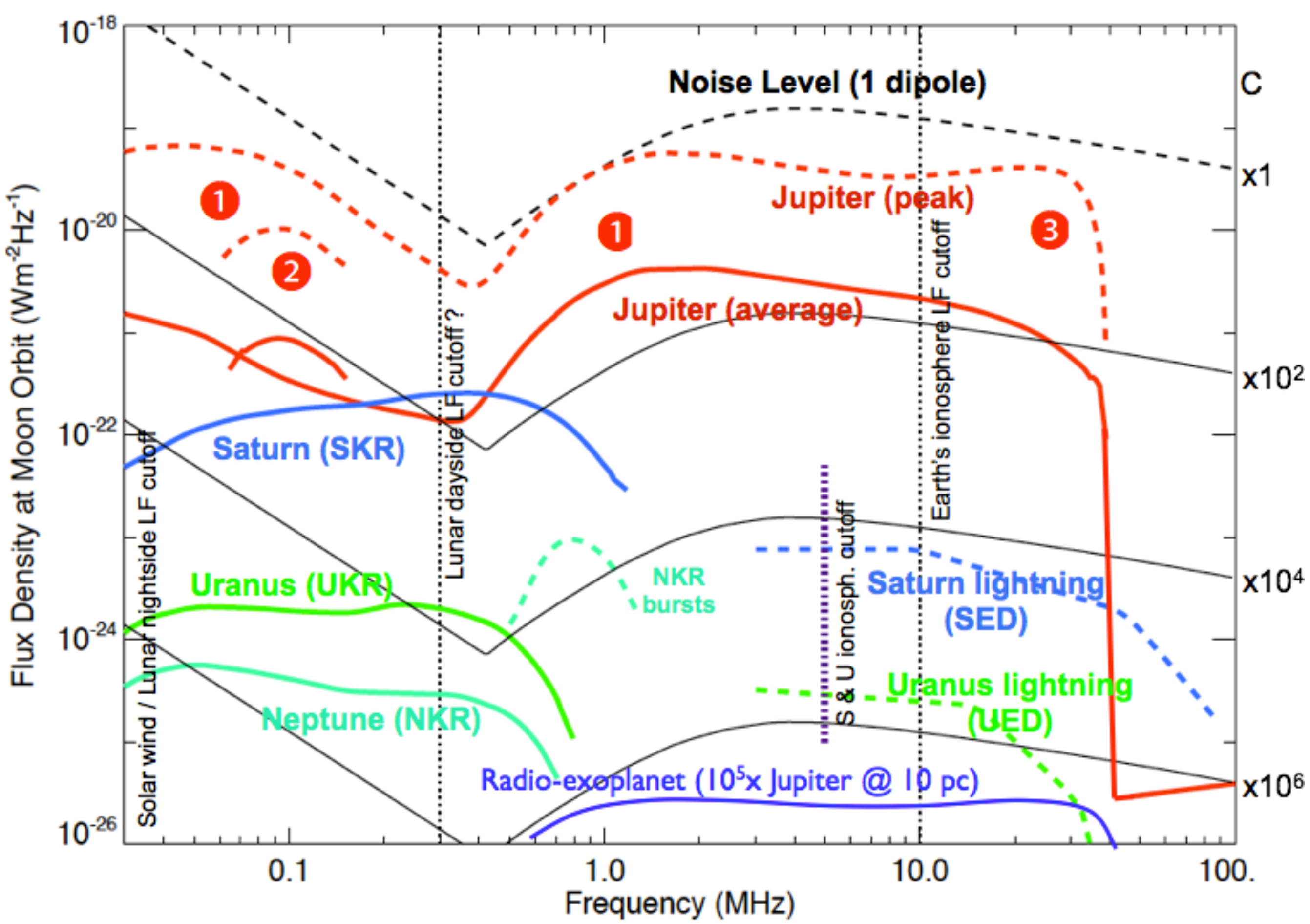
- Active: through radar scattering



Bastian et al., 2001



⑤ Auroral emissions from the giant planets' magnetospheres in our solar system: rotation periods, modulations by satellites & SW, MS dynamics, seasonal effects, ...



→ Easy detection of Jovian radio emissions with a single dipole from Earth orbit

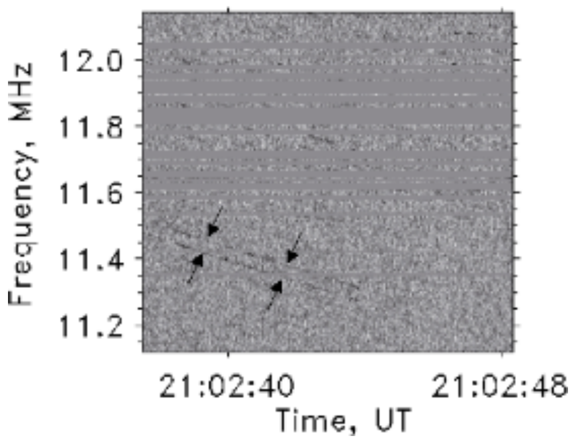
→ First opportunity in decades to study Uranus and Neptune

→ Lightning from Saturn, Uranus, Mars ?

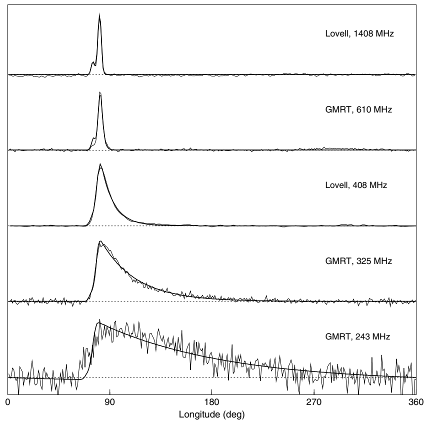
→ Exoplanets with a large array

Radio emission	Required C	N (dipoles)	b (kHz)	τ (msec)	$C = N(b\tau)^{1/2}$
Jovian magnetosphere	$10^0 - 10^2$	1 – 10	10	10	$10^1 - 10^2$
Saturn's magnetosphere	$10^1 - 10^3$	1 – 10	10	10^3	$10^2 - 10^3$
Uranus & Neptune magnetosphere	$10^3 - 10^5$	1 – 10	200	$10^3 - 10^4$	$5\times10^2 - 1.5\times10^4$
Saturn's lightning	$10^3 - 10^5$	1 – 10	2×10^4	200	$2\times10^3 - 2\times10^4$
Uranus' lightning	$10^4 - 10^6$	1 – 10	2×10^4	200	$2\times10^3 - 2\times10^4$
Radio-exoplanet $10^5\times$Jupiter at 10 pc	$10^6 - 10^7$	1 – 10	2×10^4	6×10^4 – 4×10^7	$3\times10^4 - 10^7$

⑥ Detection of pulsars down to VLF, with implications for interstellar radio propagation : LF cutoff of temporal broadening in $1/f^{4.4}$?
→ largest scale of turbulence in ISS ? limit of transient observations ?



PSR0809+74 at Kharkov UTR2
(Ryabov et al., 2010)



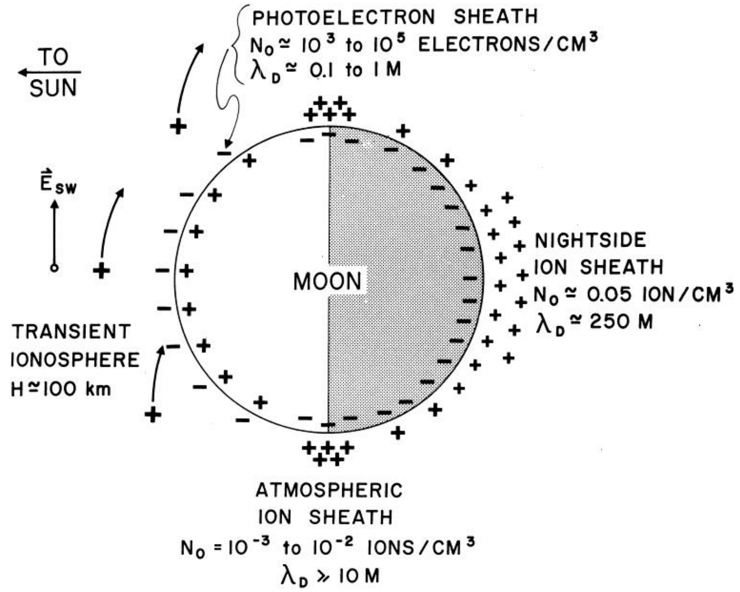
(Löhmer et al., 2004)

- Requires coherent integration over several days

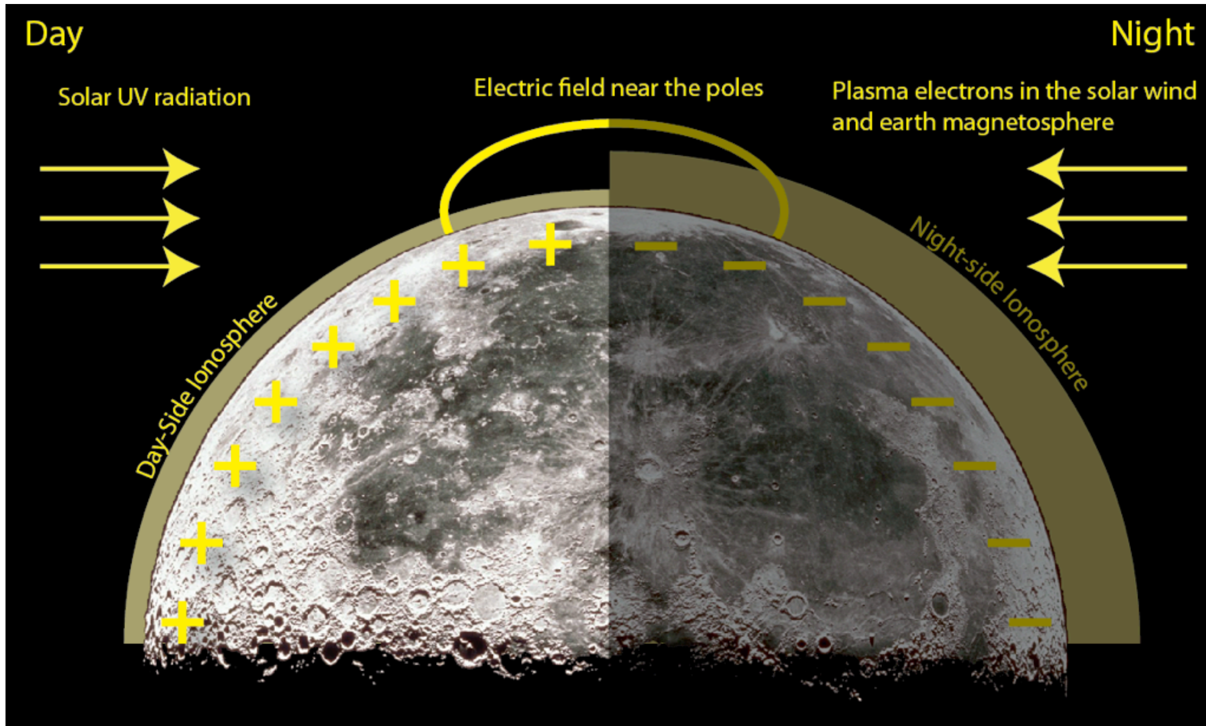
⑦ The unknown, Moon environment, Pathfinder technology demonstration …

Automatic by-product of LF radio astronomy measurements :
→ characterization of the (local) lunar e.s., e.m. & plasma environments, incl.

- f_{pe} (LT,solar activity, traversal of Earth's magnetotail)
- e.s. discharges from regolith charging
- Properties of lunar subsurface wrt radio waves



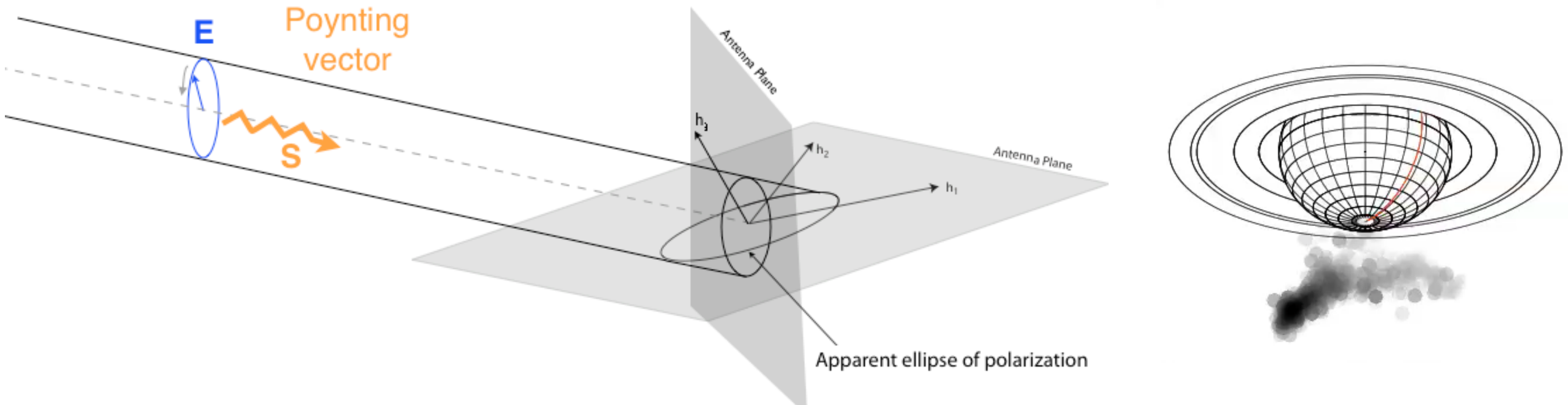
(Klein-Wolt et al., 2012)



Day and night difference on a lunar polar location: solar UV radiation causes the lunar surface to be positively charged on the day-side (a few Volts, extending up to ~1meter in height), on the night-side the interaction with plasma electrons (from the solar wind and the earth's magnetosphere) causes the surface to become negative (~100V, extending up to ~1 km). This causes a strong electric field on the south and north pole. In addition the moon is constanty exposed to micrometeorites and cosmic rays.

① INITIAL STEP : a few electric dipole/monopole antennas, a few m long

→ spectrometry of local environment, lunar ionosphere + subsurface, first radio measurements (or upper limits) on intense emissions, foregrounds, Sun, Planets, bursts, propagation effects…
→ assess antennas, deployment/robotic installation, power, day/night operation, onboard computing, data storage, communication (on the Moon and to Earth) …
→ 2 co-located crossed dipoles + dual-input receiver : GonioPolarimetry + low-resolution (°) sky mapping



Goniopolarimetry principle and results at Saturn (Cassini)

→ + ≥1 widely separated dipole & waveform capture permits interferometry, global sky average mapping
→ + sounder permits Ground Penetrating Radar, probing the subsurface

- Ideal mission = 2 widely separated landers on Lunar Farside + relay at Moon-Earth L2 = Farside Explorer concept
- Minimum mission = 1 lander near Lunar South Pole (no relay) = ESA Lunar Lander concept

- Possible VLBI measurements with ground-based instruments (LOFAR ...)
- Potential collaboration in all areas
- Strong heritage at LESIA (receivers on Cassini, Stereo..., TRL~6-7) and with LOFAR

② Step 2: ~100 antennas ($A_{eff}=\lambda^2/k \sim 3\times10^4$ m^2 @ 10 MHz, $\lambda\sim30$ m)

Separation D = 1 - 1000 km
- Near or Far side

→ Resolution (λ/D): ~1.6° (D=1 km, 10 MHz), 6''-1' (D=1000 km, 10-1 MHz)
→ Sky mapping, Solar and Planetary studies, Pulsars and propagation

③ Step 3: ~1000-10000 antennas = LOFAR-on-the-Moon

- Far side Lunar Radio Array

→ Cosmology, Exoplanets