LONG WAVELENGTH RADIO ASTRONOMY & LUNAR EXPLORATION

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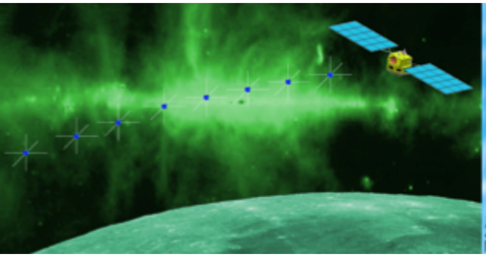
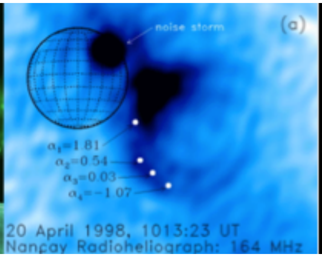
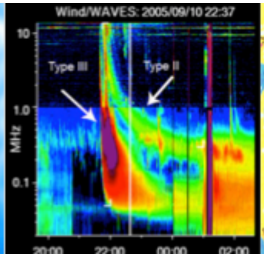
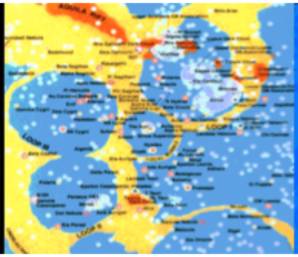
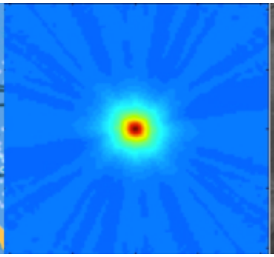
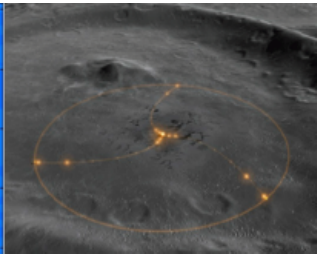
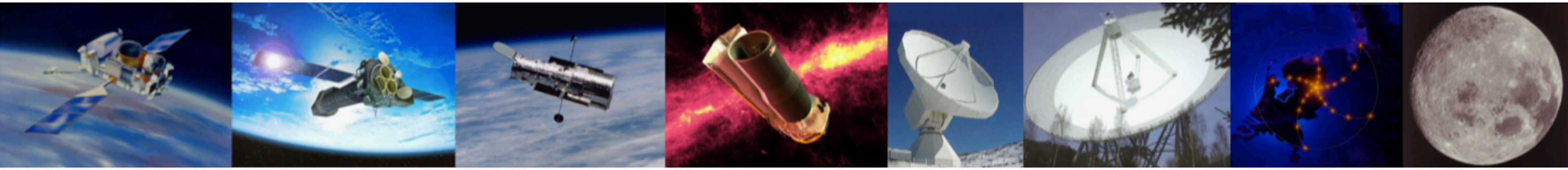
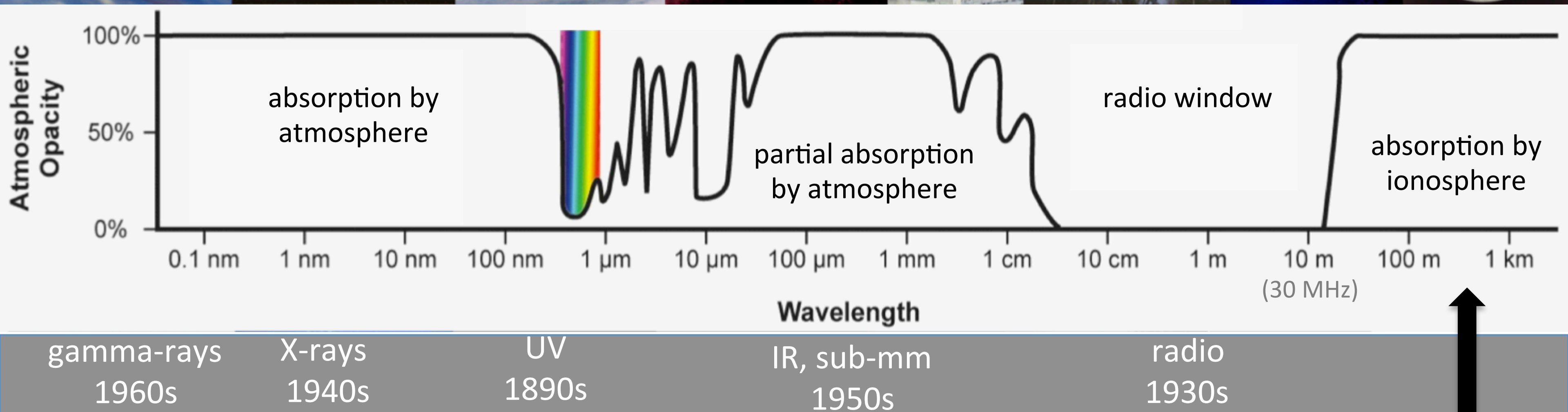





Motivation for Space / Moon:
RF absorption by the ionosphere





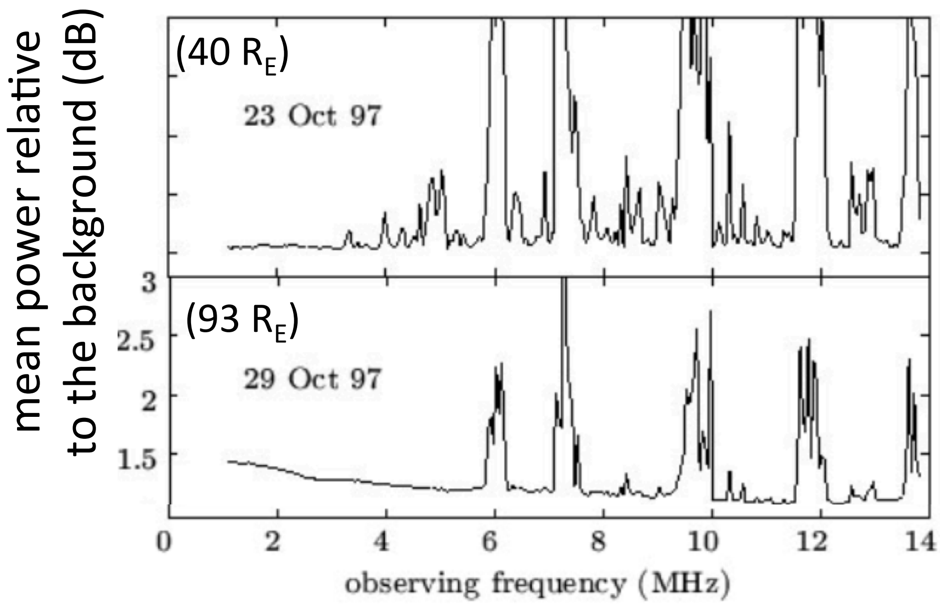
Terra incognita of cosmic electro-magnetic emission

Aim: opening-up the last remaining unobserved window at decameter and longer wavelengths (frequencies below ~30 MHz)

➔ exciting and "guaranteed" science + investigation of the unknown

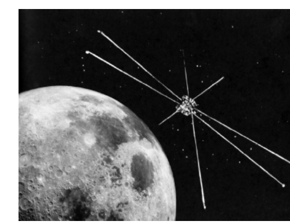
Motivation for Space / Moon: Terrestrial radio interference

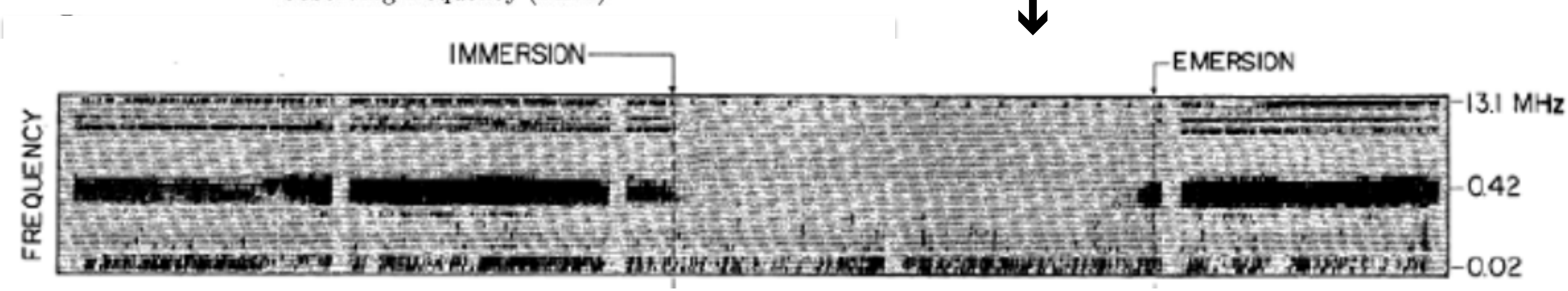
Radioastronomy on the Moon is an old idea. First proposals pre-date Apollo missions !



typical human-made interference received by the NASA-WAVES Instrument on Wind, averaged over 24 hours (0.7 resp. 1.6 x Earth-Moon dist.)

RAE-2 occultation of Earth, 100 minute observation (x-axis: time) on December 12th 1973, at 1100 km lunar orbit

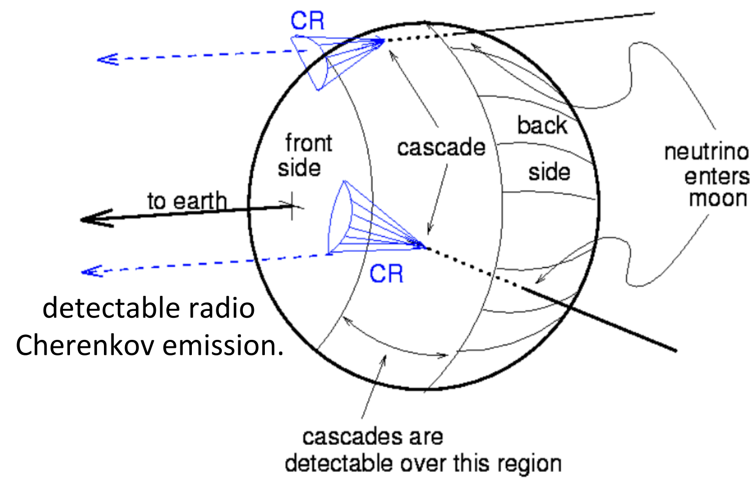




Motivation for Space / Moon: specific "Lunar" science & astro-particle physics

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

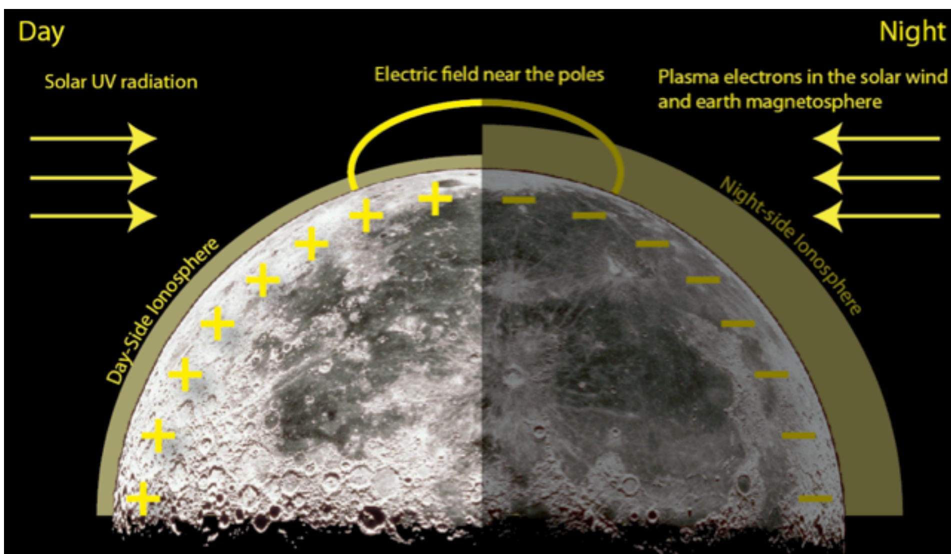
- f_{pe} (LT, solar activity, traversal of Earth's magnetotail)
- e.s. discharges from regolith charging
- Properties of lunar subsurface wrt radio waves



Astroparticle physics:

- Ultra-high energy elementary particles with energies a billion times higher than at CERN hitting the Moon!
- They are rare and one needs a large detector volume …

⇒ The Moon is by far the largest particle detector available for astroparticle physics!



Science: cosmology

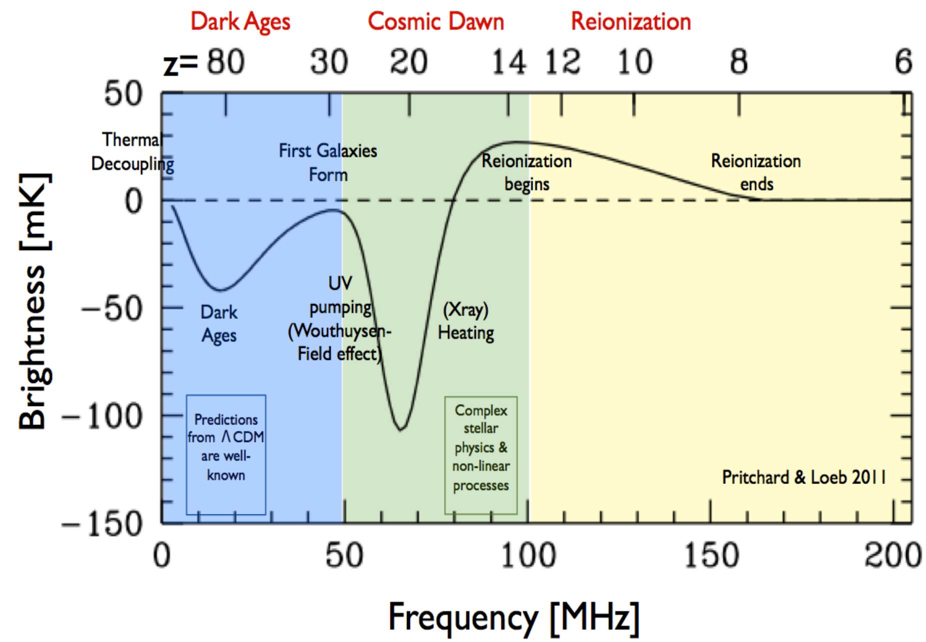
Cosmology : pathfinder measurements of the red-shifted HI line that originates from before the formation of the first stars (dark ages, reionization), e.g. DSL (order 10 elements)
Signal ~10^{-6} x galactic background → requires extreme quietness & long integrations

At ν~70/20 MHz, the system temp. $T_{sys} \sim T_{sky} \sim$ 2500/60000 K. One needs to reach ~10/5 mK for a 10-σ detection of a -100/-50 mK signal

The integration times can be approximated as follows:

$$t_{\rm int} = 17\ {\rm hr} \times \left(\frac{\nu}{70\ {\rm MHz}}\right)^{-5.1} \left(\frac{\Delta\nu}{1\ {\rm MHz}}\right)^{-1} \left(\frac{\delta T}{10\ {\rm mK}}\right)^{-2}$$

$$t_{\rm int} = 170\ {\rm day} \times \left(\frac{\nu}{20\ {\rm MHz}}\right)^{-5.1} \left(\frac{\Delta\nu}{10\ {\rm MHz}}\right)^{-1} \left(\frac{\delta T}{5\ {\rm mK}}\right)^{-2}$$



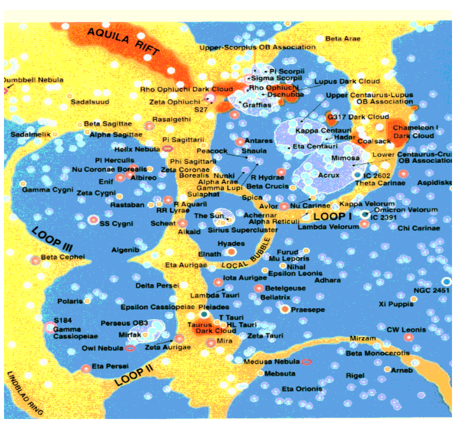
Hence if the width of the signal exceed ~1/10 MHz, one can reach ~10/5 mK in t_{int} less than one day/year, but the required spectral DR ~ 10^7 needs an extremely accurate band-pass calibration. This is one of the major challenges of ALL (ground/space based) low-frequency global-signal experiments.

L.Koopmans
DSL2015 workshop
Dwingeloo

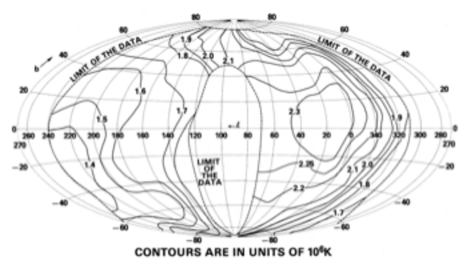
Science: sky mapping

Long wavelength sky mapping + monitoring :

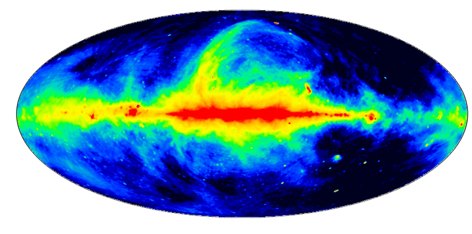
- radio galaxies, large scale structures (clusters with radio halos, cosmological filaments, …), including polarization, down to a few MHz
- Weak refraction/scintillation by ionosphere as compared to ground-based observations
- Interstellar & interplanetary media broaden sources to ~1’ at 30 MHz, ~1° at 1 MHz
- free-free absorption results in a foggy sky <1-2 MHz, but there are holes in the fog
- Imaging capabilities best with a lunar/space-based Radio Array
- Precursor measurements 1-2 Landers (or 1 + Rover) : GonioPolarimetry + Global inversion of Interferometric Visibilities



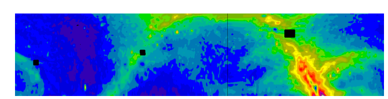
ISM “tomographic” view, the “local bubble”



(Novaco & Brown 1978)
4.7 MHz (1.31 not shown)



Haslam et al, 1982
all-sky survey at 408 MHz

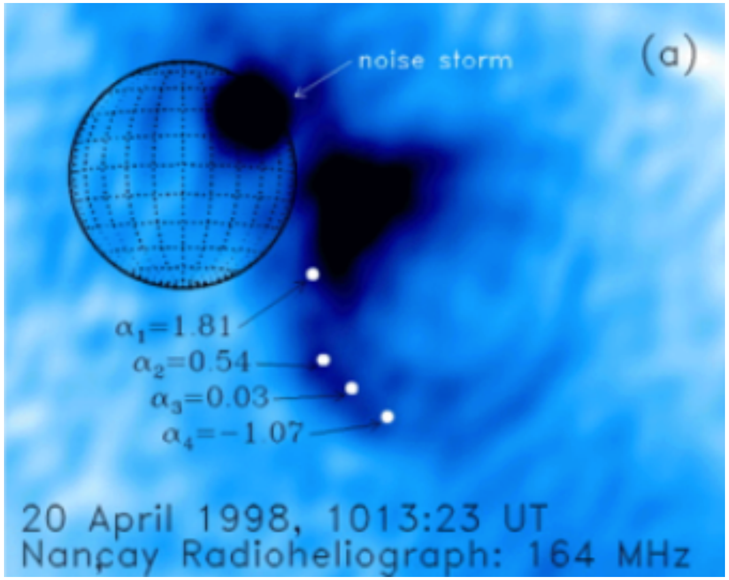


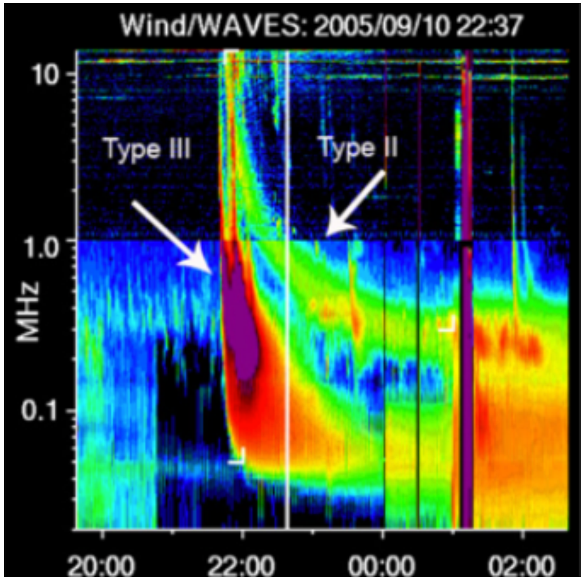
DRAO sky map @ 22 MHz

Science: heliopysics & space weather

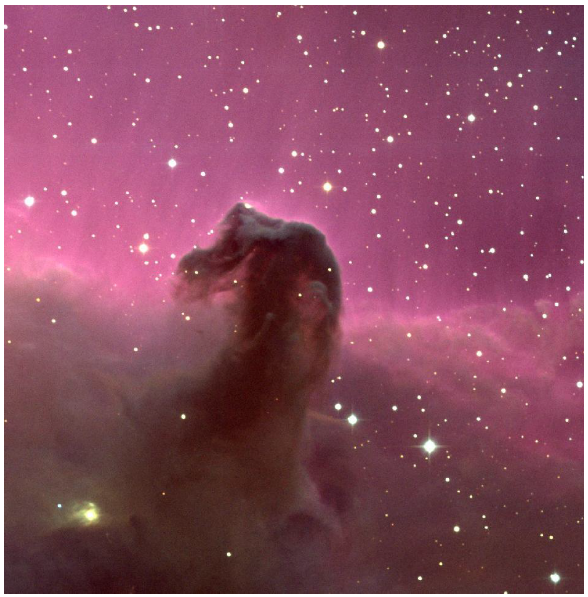
Heliophysics
- Imaging Solar activity at lower frequencies <10 MHz), resolution >10 pixels
- Imaging Type II (slow) & III (rapid) bursts
- Optional: imaging & tracking of CMEs beyond Earth distance

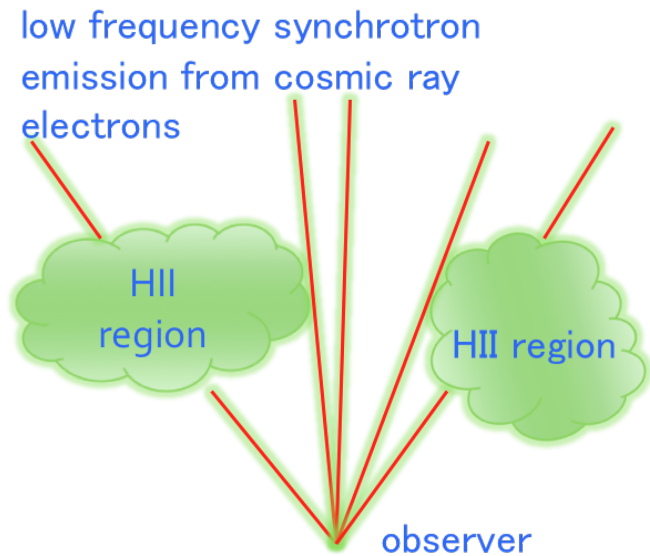
Space weather:
- passive: through scintillation and Faraday rotation
- active: through radar scattering





Science:
interstellar medium and origin of cosmic rays



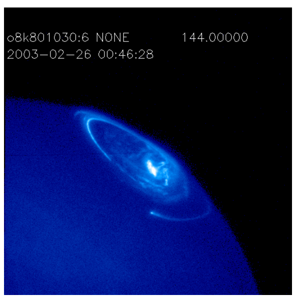


HII region is opaque to low frequency (a few MHz) synchrotron emission from cosmic ray electrons. So, observing the HII region enables determination of cosmic ray in that short l.o.s., helps address the quest on the origin of cosmic ray.

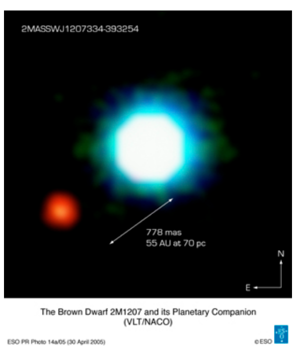
Science: planetary emissions

Lightning and auroral emissions from the giant planets' magnetospheres in our solar system: rotation periods, modulations by satellites, seasonal effects, ...

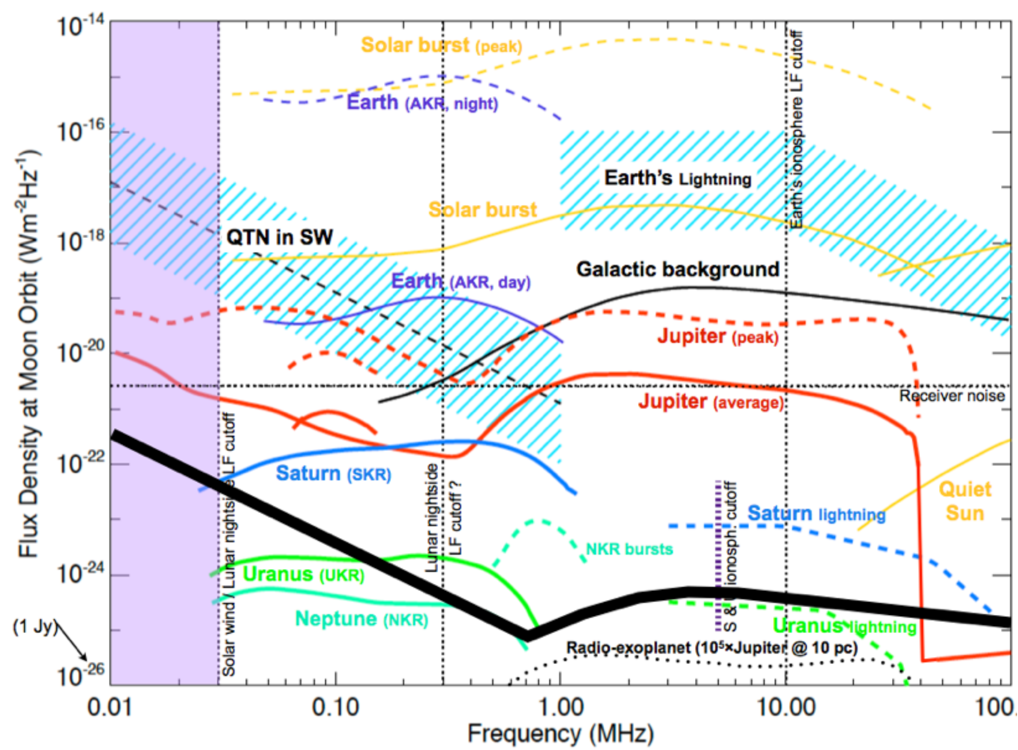
- easy detection of Jovian radio emissions with a single dipole
- first opportunity in decades to study Uranus and Neptune
- lightning from Saturn, Uranus, Mars ?
- exoplanets with a large array



Jupiter-like flares

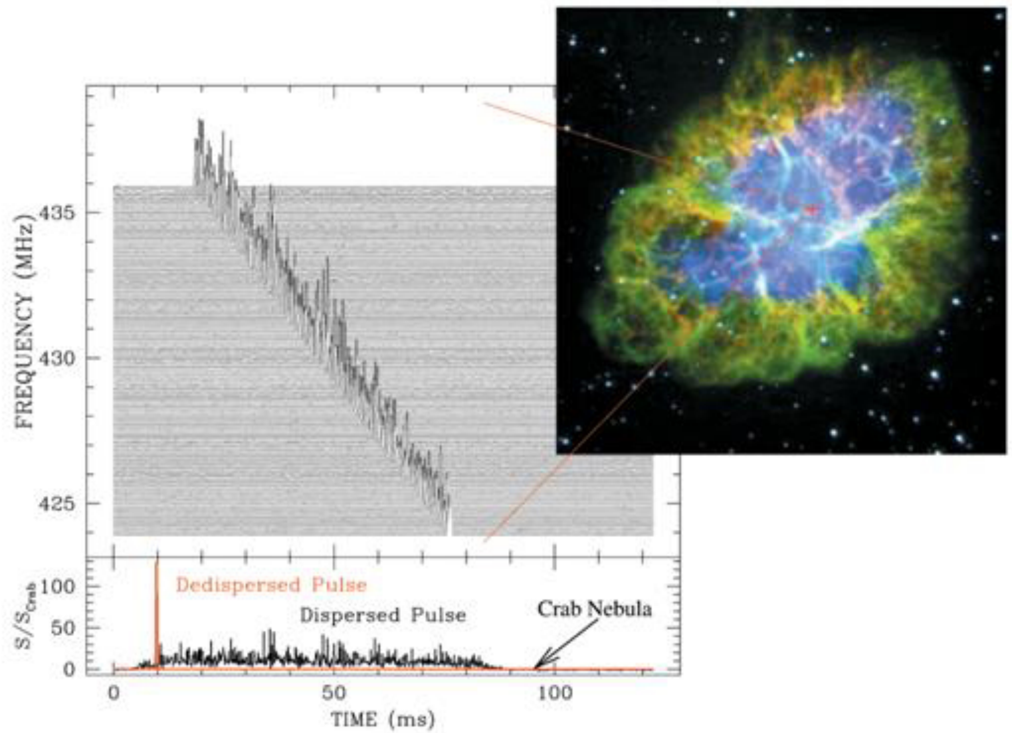


extra-solar planetary bursts

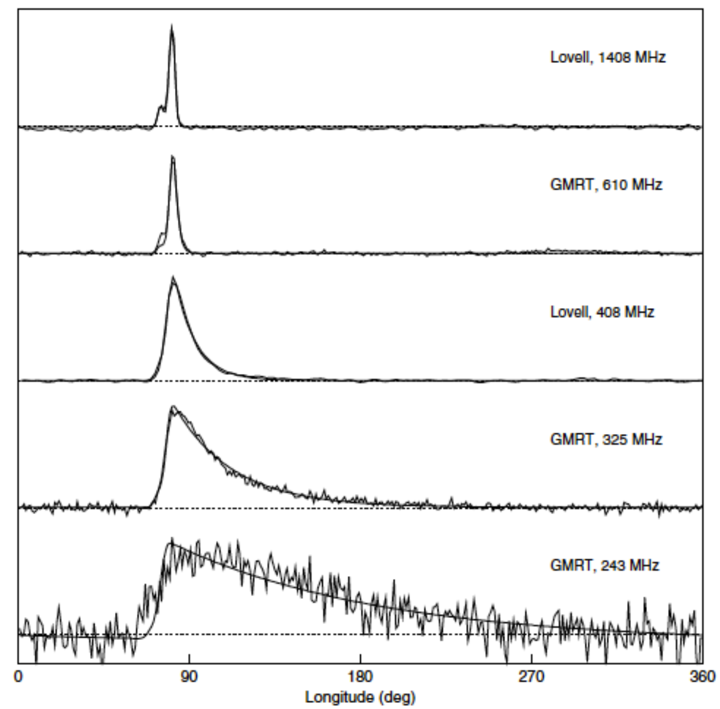


Science: transients

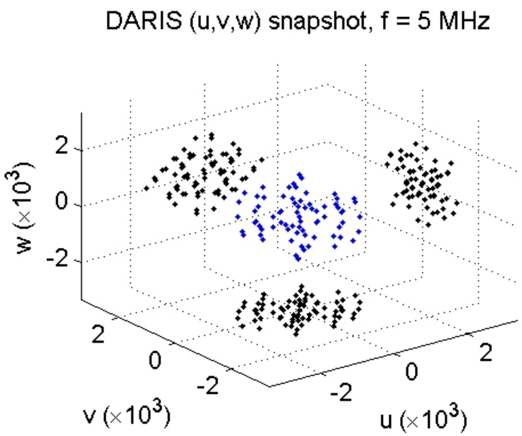
Transients (Jupiter-like flares, Crab-like pulses, extra-solar planetary burst, etc)

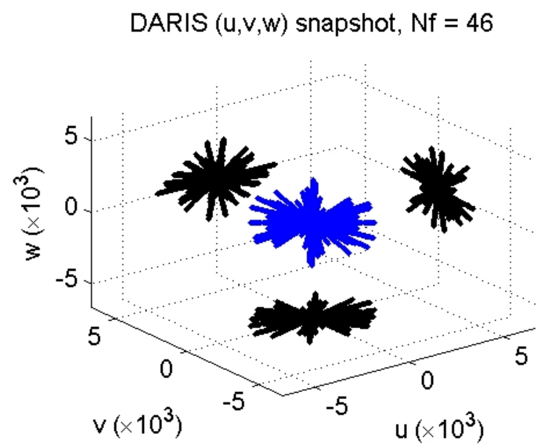


Detection of pulsars down to VLF, with implications for interstellar radio propagation:
LF cutoff of temporal broadening in $1/f^{4.4}$?



Aperture sampling and PSF



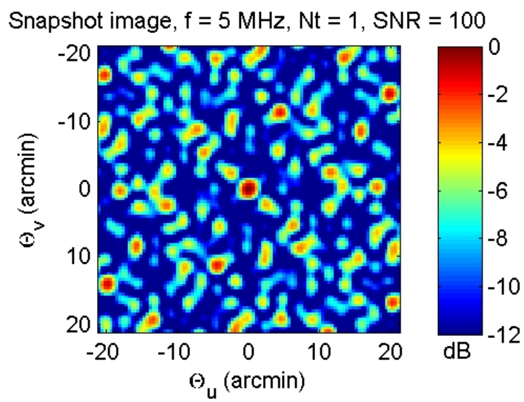


Aperture (u,v,w) filling - left and simulated one-source sky maps (PSF) – below

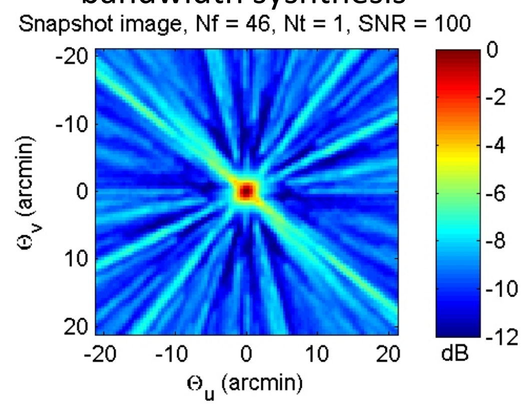
(u,v,w) definition:

$$\mathbf{r_i}(t_n) - \mathbf{r_j}(t_n) = \lambda \left[u_{ij}(t_n), v_{ij}(t_n), w_{ij}(t_n) \right]^T$$

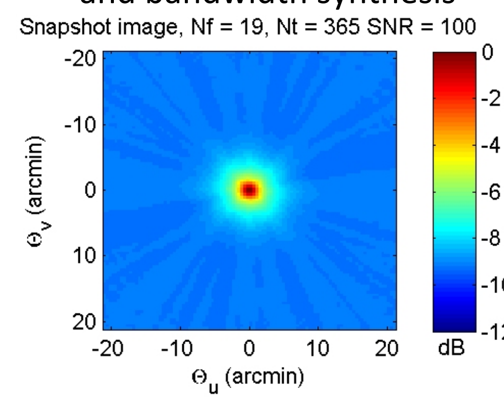
1s snapshot image



1s snapshot image and bandwidth sysnthesis



multiple snapshot images and bandwidth synthesis



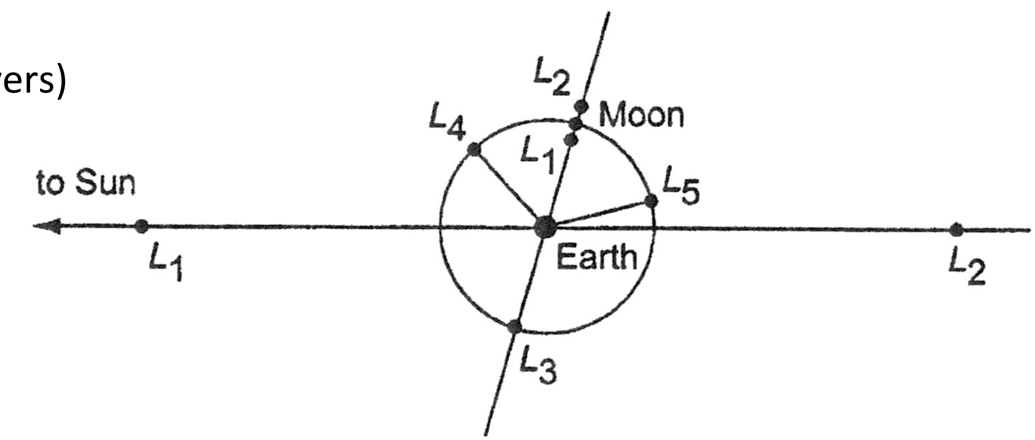
Narrow band condition: $\Delta f \ll 1/(2\,\pi\,\tau_{ij})$ or Δf=1 kHz for baseline up to 100 km
Time smearing: integration time: baselline change << λ

Locations

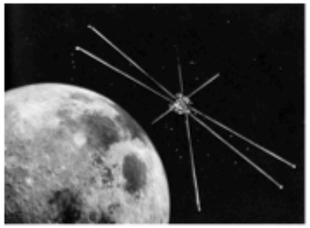
Possible orbits:	RFI	(uvw) filling	downlink bw
• Earth orbit	-	+	++
• Earth GTO	-/+	+	++
• **Lunar orbit (L2, low alt.)**	**+/- ++**	**+**	**+**
• Sun-Earth L4/L5	+++	-	-
• Dynamic Solar orbit	++	-	+/-
• Sun-Earth L2	+/- +	-	+
• **Lunar far-side**	**+++**	**+**	**+**

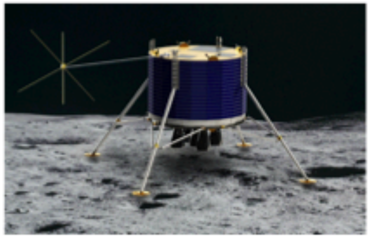
Considerations:

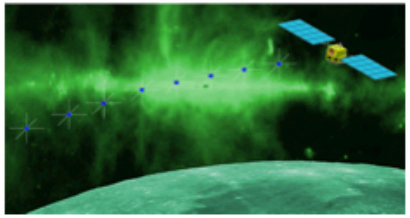
- Astronomical science
- RFI from Earth
- Integration time, range rate
- Constellation control (for free flyers) (abs. and rel. position)
- Downlink bandwidth to Earth
- Cost (mass, propulsion)

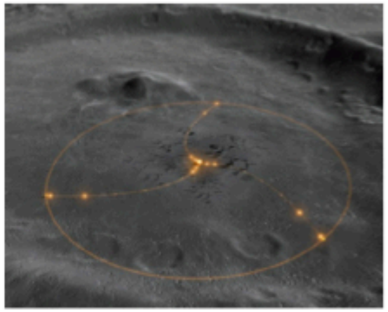


Possible next steps
expandable – step-wise approach









One electric dipole / tripole / monopole antennas, a few m long

Lunar orbit or on lunar surface (e.g. Chang'e 4, LRX concept)

- spectrometry of local environment, Sun, Planets, bursts, propagation effects…
- GonioPolarimetry + low-resolution (°) sky mapping
- Possible VLBI measurements with ground-based instruments (LOFAR ...)

Two element interferometer (lunar orbit or on lunar surface)

- widely separated dipole & waveform capture permits interferometry, global sky average mapping

~ 10 antenna cluster in lunar orbit (e.g. DSL, OLFAR, DARE concepts)

- Sky mapping, Solar and Planetary studies, Pulsars and propagation
- broad range of science cases, detailed sky maps

~100 antennas ($A_{eff}=\lambda^2/k \sim 3\times10^4$ m^2 @ 10 MHz, $\lambda \sim 30$ m)

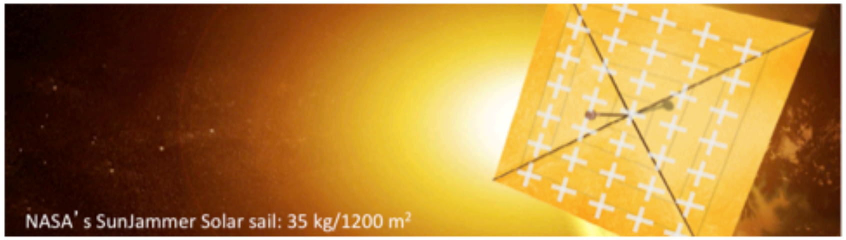
Separation D = 1 - 1000 km, lunar near or far side of close to polar regions

- 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
- Cosmology, Exoplanets

~1000-10000 antennas = LOFAR-on-the-Moon

- far side Lunar Radio Array
- novel concepts e.g. "etched foils" in space

Potential collaboration in all areas; strong heritage



Conclusions

- ✦ Space instrumentation is required for radio astronomy, cosmology, and planetary sciences below ~15 MHz
- ✦ A long wavelength radio array can open up the last unexplored wavelength range in astronomy
- ✦ Huge interest for all astronomy communities (from cosmology to planetary sciences, and exploration of the unknown)
- ✦ Science topics: Solar System, Local Bubble, (Exo)-Planets+Transients, Surveys, Astroparticle Physics, Dark Ages
- ✦ Large scale interferometer is the goal
- ✦ Pathfinder experiments: lunar surface (far side) or lunar orbit
- ✦ Many projects on the roadmap (DSL, Farside Explorer, DARE, DEx, FOAM, OLFAR,...)
- ✦ The moon is unquestionably the very best site for a long wavelength array: large stable ground, no ionosphere, shielding from Earth+Sun interference (unique!)
- ✦ Combine distributed antenna boxes with other "payloads": seismic sensor network, X-ray Antenna box, ...