Riding Big Waves

Radio Telescopes on the Moon – Opening the last unexplored frequency window

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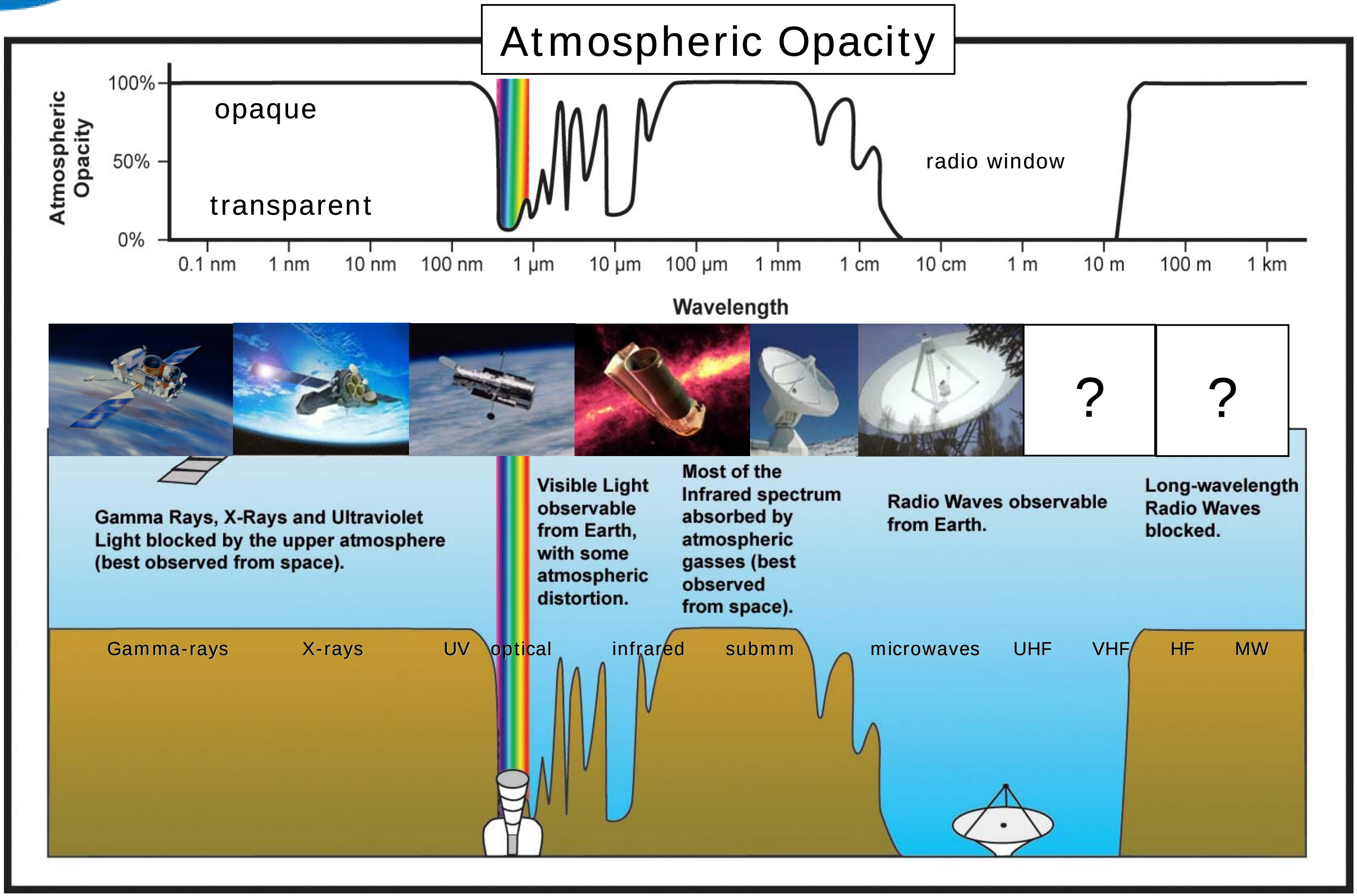
Why radio on the moon?



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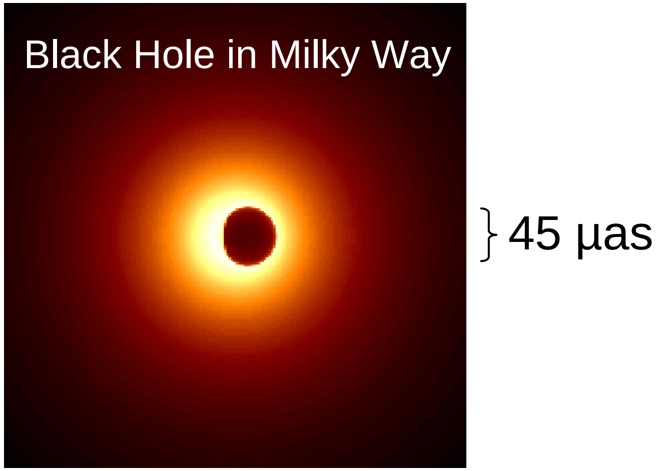
Black Hole Imaging with THz Interferometry

- The emission of the black hole in the Galactic Center peaks in the THz range.
- The emission comes from directly near the event horizon!
- Imaging may require THz a interferometer in space:
  - Baseline: ~2000 km
  - Dish size: ~4 m
  - Number: ≥5



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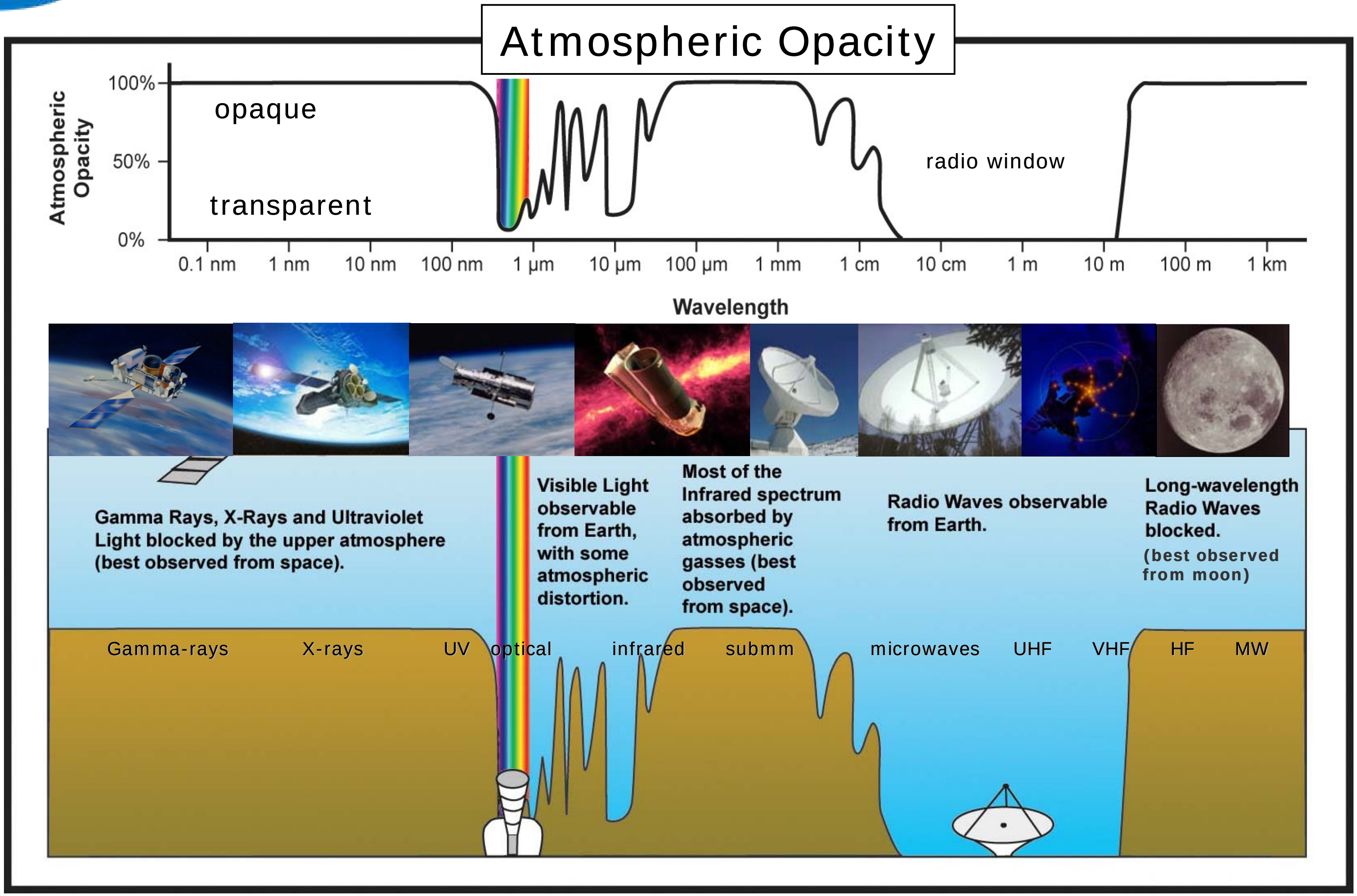

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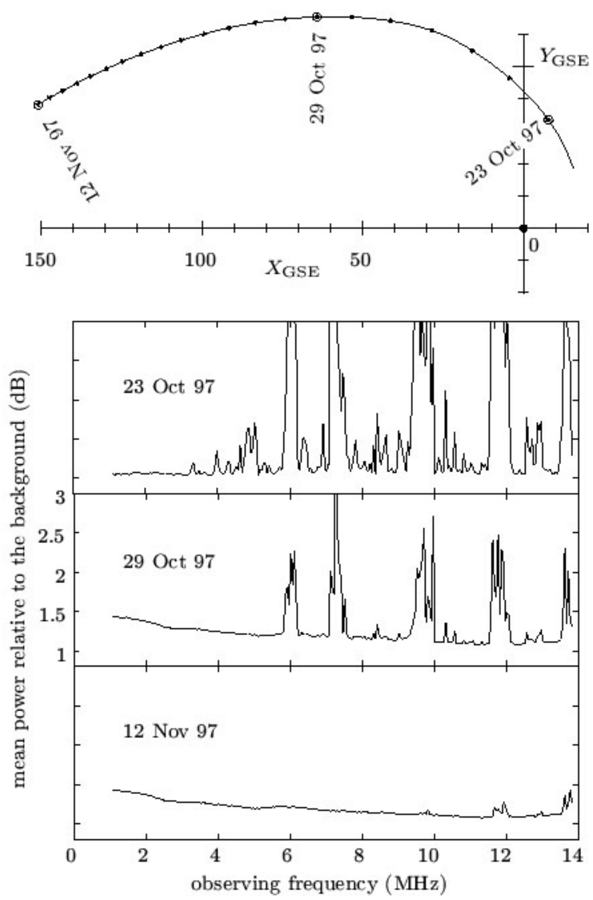
Terrestrial Radio Interference

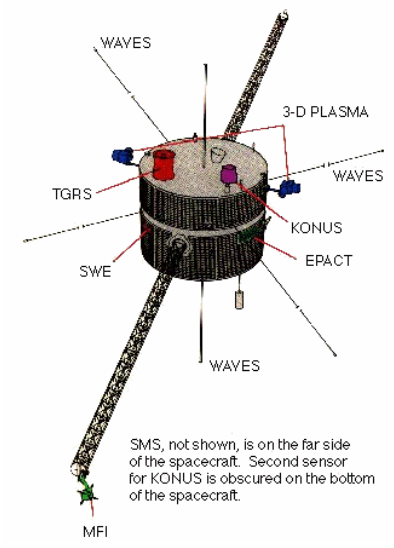


Typical man-made interference received by the WAVES instrument on Wind, averaged over 24 hours. Orbital dimensions in Earth radii.

40 Earth radii

93 Earth radii

157 Earth radii



G. Woan from ESA study SCI(97)2

RAE-2 lunar occultation of Earth

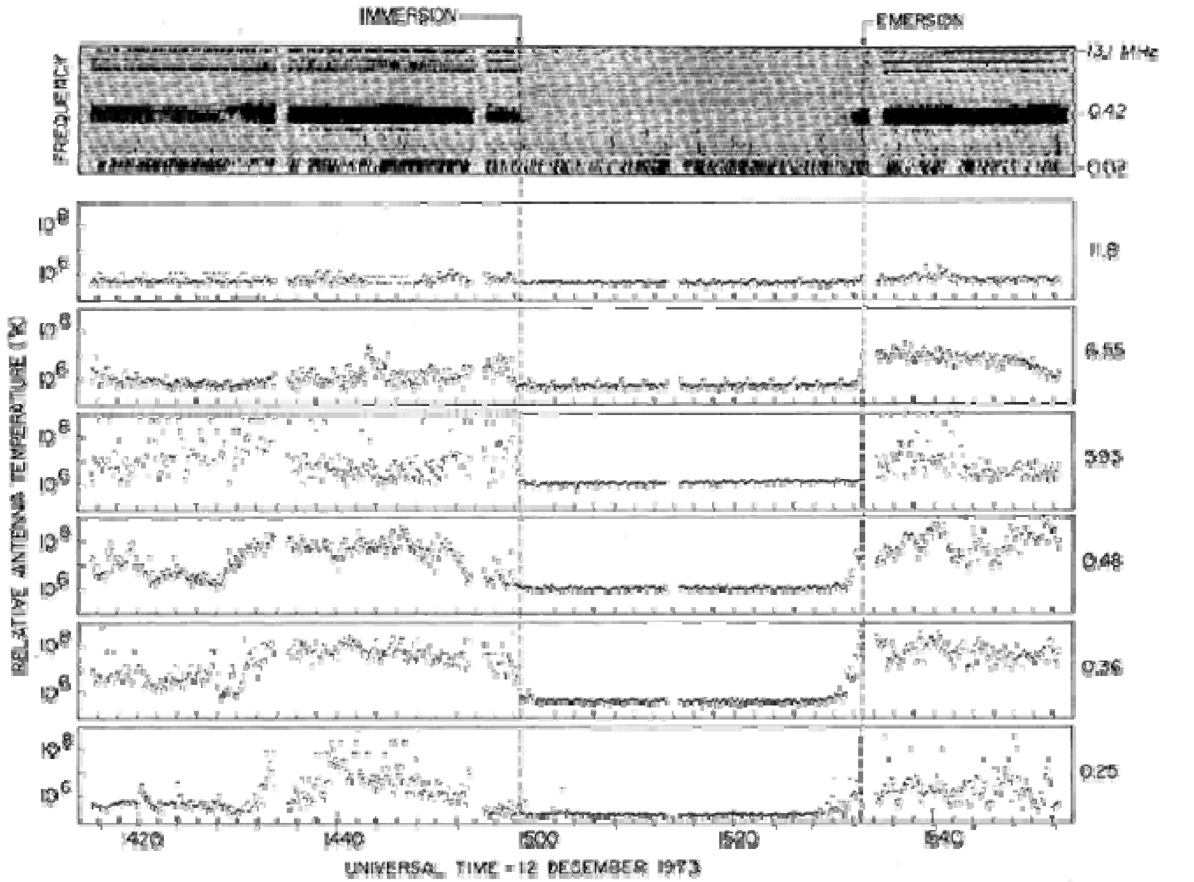
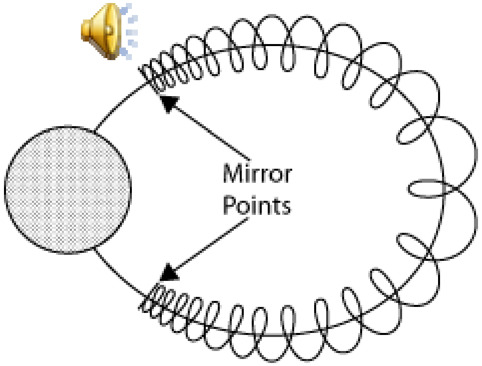
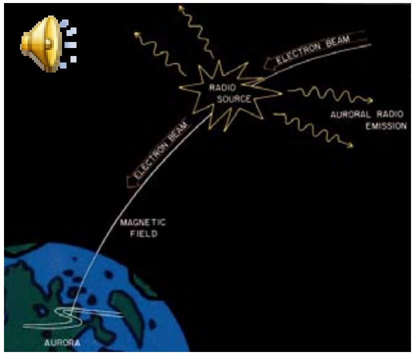


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver and the burst receiver are tuned to the same frequency.





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Good “news”: The Moon is radio-protected for astronomy!

- The back side of the moon is declared as a radio protected site within the ITU Radio Regulations
  - The IT Radio Regulations are an international treaty within the UN.
  - Details are specified in a published ITU Recommendation (this is a non-mandatory recommendation, but is typically adhered to).

⇒ Radio astronomy on the moon has been a long-standing goal, protected by international treaties!

⇒ Steps need to be taken to protect the pristine and clean nature of the moon.

⇒ Lunar communication on the far side needs to be radio quiet.

ARTICLE 22
(ITU Radio Regulations)
Space services

Section V – Radio astronomy in the shielded zone of the Moon

22.22 § 8 1) In the shielded zone of the Moon[31] emissions causing harmful inter-ference to radio astronomy observations[32] and to other users of passive services shall be prohibited in the entire frequency spectrum except in the following bands:

22.23 *a)* the frequency bands allocated to the space research service using active sensors;

22.24 *b)* the frequency bands allocated to the space operation service, the Earth exploration-satellite service using active sensors, and the radiolocation service using stations on spaceborne platforms, which are required for the support of space research, as well as for radiocommunications and space research transmissions within the lunar shielded zone.

22.25 2) In frequency bands in which emissions are not prohibited by Nos. **22.22** to **22.24**, radio astronomy observations and passive space research in the shielded zone of the Moon may be protected from harmful interference by agreement between administrations concerned.

22.22.1 The shielded zone of the Moon comprises the area of the Moon’s surface and an adjacent volume of space which are shielded from emissions originating within a distance of 100 000 km from the centre of the Earth.

32 **22.22.2** The level of harmful interference is determined by agreement between the administrations concerned, with the guidance of the relevant ITU-R Recommendations.

Current Status at Long Wavelengths

Extremely poor resolution, strong diffuse Galactic emission

T_{sys}	freq (MHz)
3.3×10^5	10
2.6×10^6	5
2.0×10^7	1
2.6×10^7	0.5
5.2×10^6	0.25

galactic synchrotron emission (10 to 1 MHz)

free-free absorption (0.5 to 0.25 MHz)

RAE-2 observations, Novaco & Brown 1978

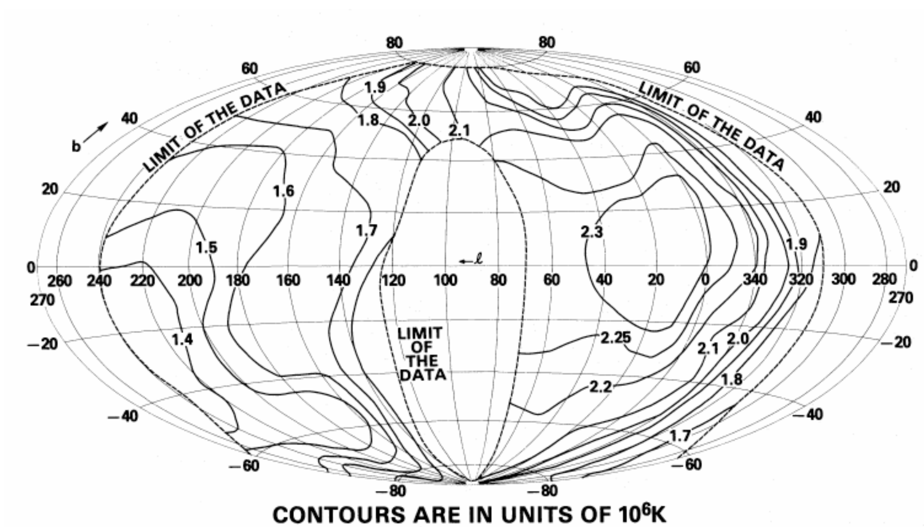


FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

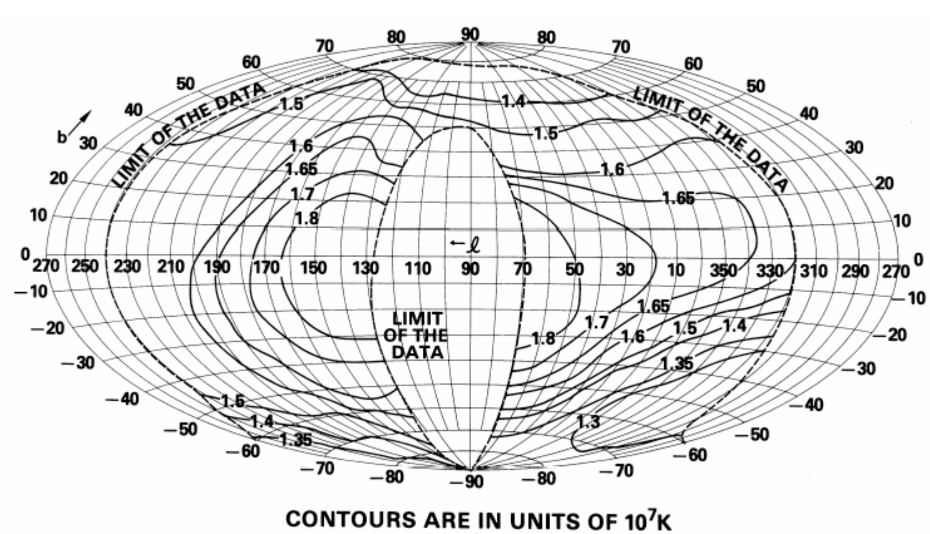
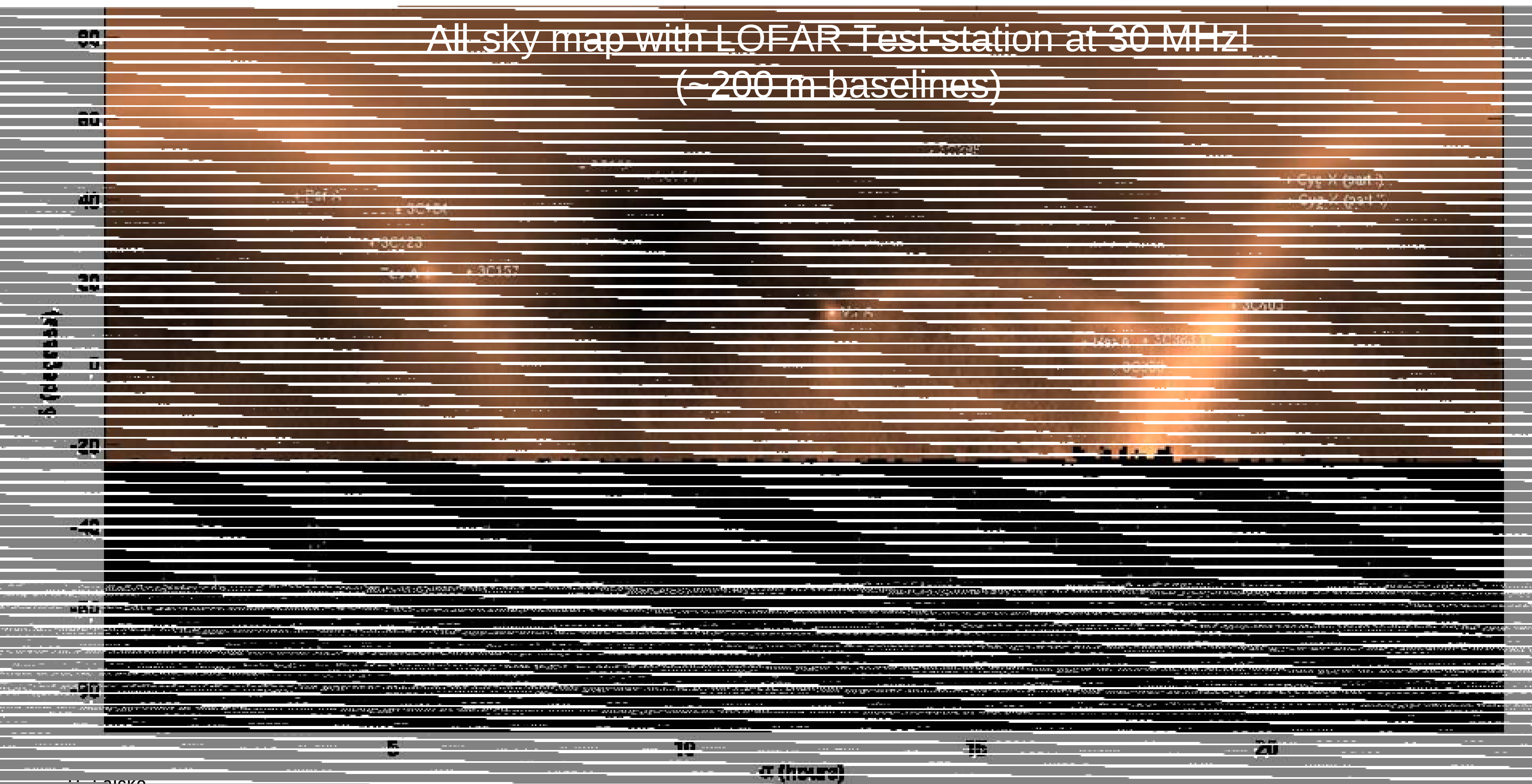


FIG. 8.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 1.31 MHz

slide from G. Woan

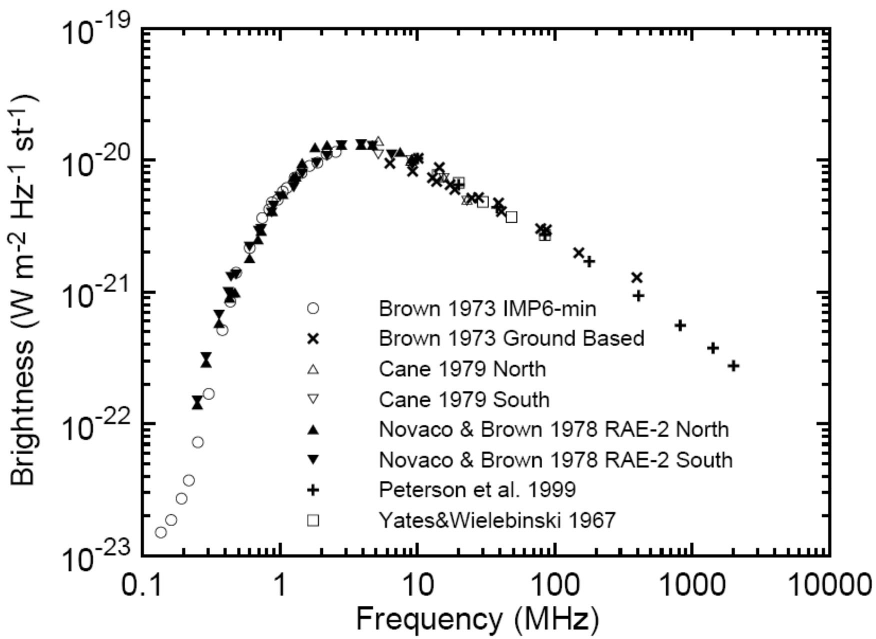
Current Status at Long Wavelengths

Array of cheap dipoles can improve image quality significantly



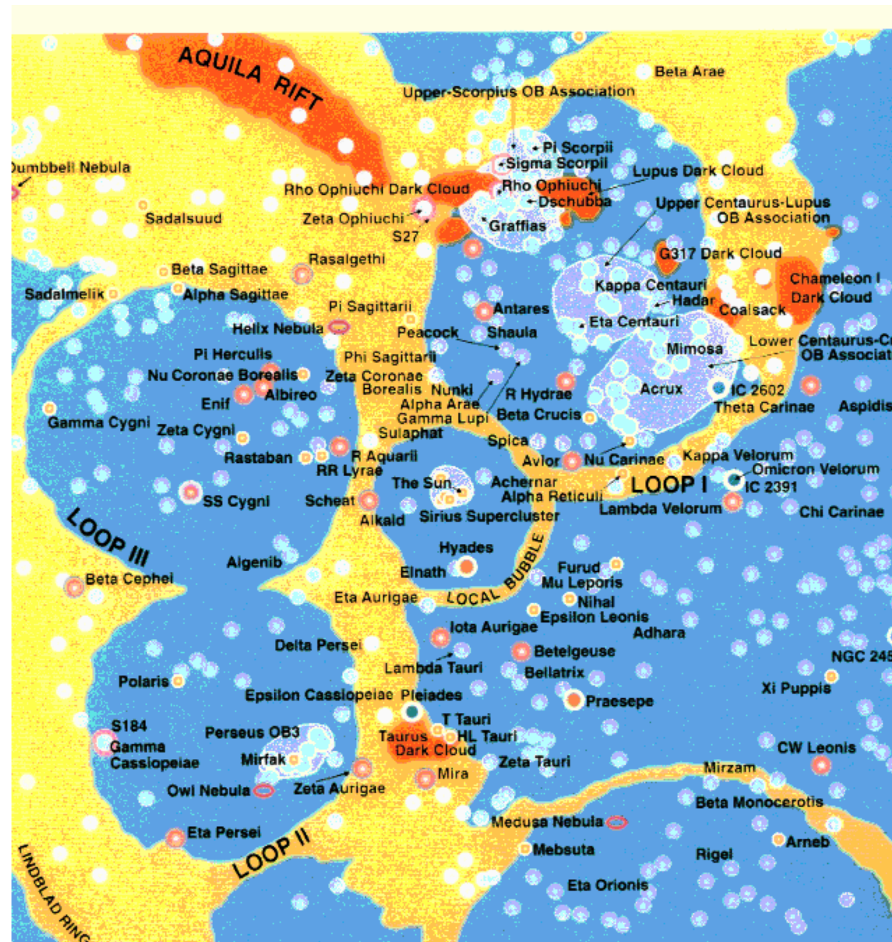
Low Frequency Radio Spectrum

- Dominated by emission from cosmic ray electrons in the Milky Way
- Milky Way becomes optically thick below 2-3 MHz
- Science:
  - > 3 MHz: Extragalactic Surveys
  - <3 MHz „Local Bubble“ 3D Tomography



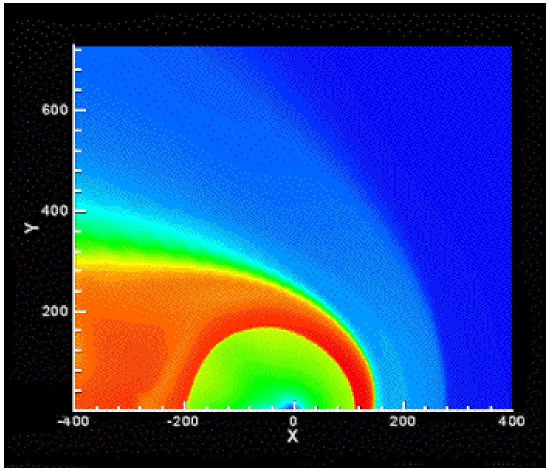
The Local Bubble and the Warm Interstellar Medium (WIM)

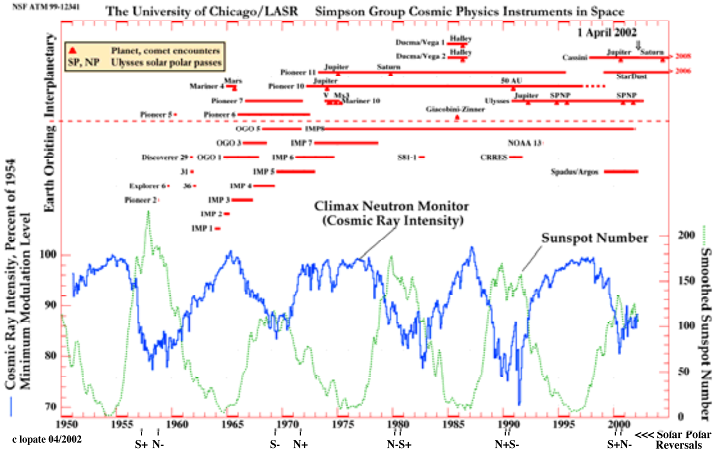
- The Galaxy is embedded in a warm (10000K) interstellar medium causing low-frequency radio absorption.
- The inner 1500 lightyears around the sun are highly structured ("swiss cheese") due to supernova explosions and star formation.
- We are living in a low density "bubble".
- By stepping through LF frequencies we can see the shells closer and closer to the solar system with unprecedented detail.

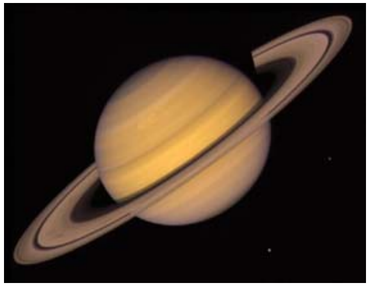


Heliosphere, Local Bubble and Earth Climate

- The Heliosphere is the bubble blown by the solar wind.
- At the shock between heliopshere and Milky Way gas (WIM) anomalous cosmic rays are accelerated.
- These cosmic rays are suspected to influence Earth climate and cloud formation (a hotly debated topic)
- The strength of solar wind and WIM density strongly influence the cosmic ray flux and hence likely also climate and life on Earth.

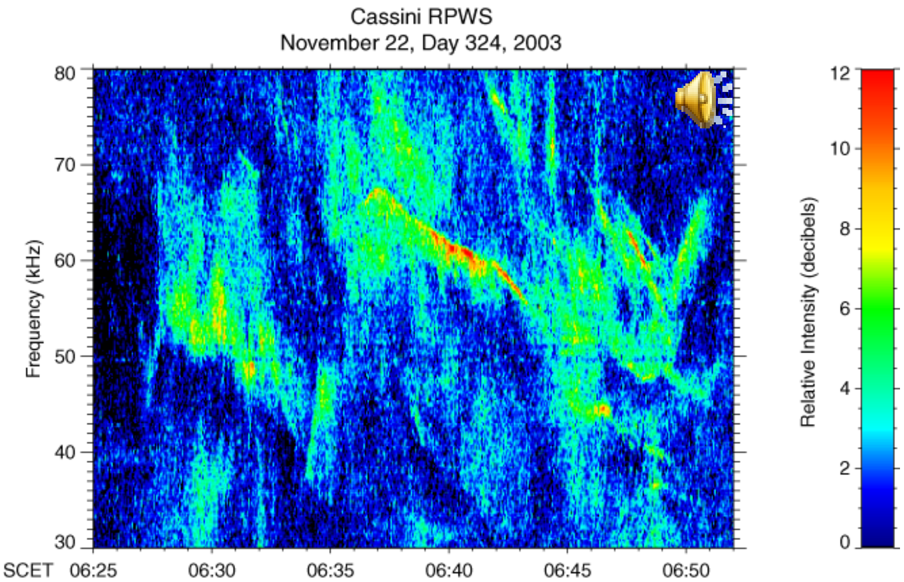




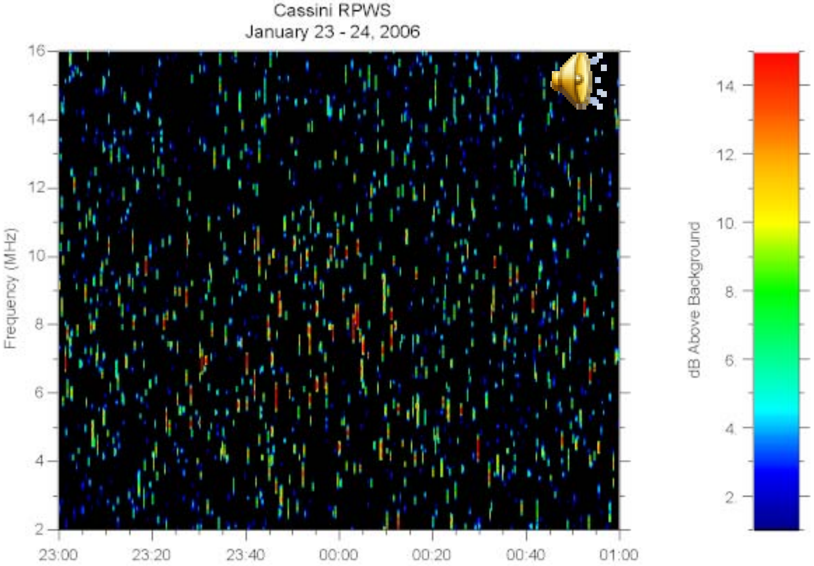


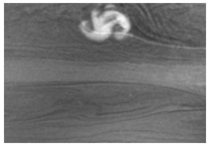
Sounds of Saturn from Cassini Space Craft

aurora



lightning in giant thunder storm





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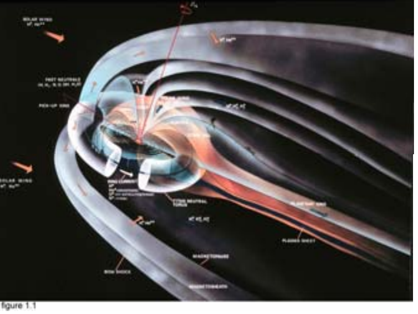
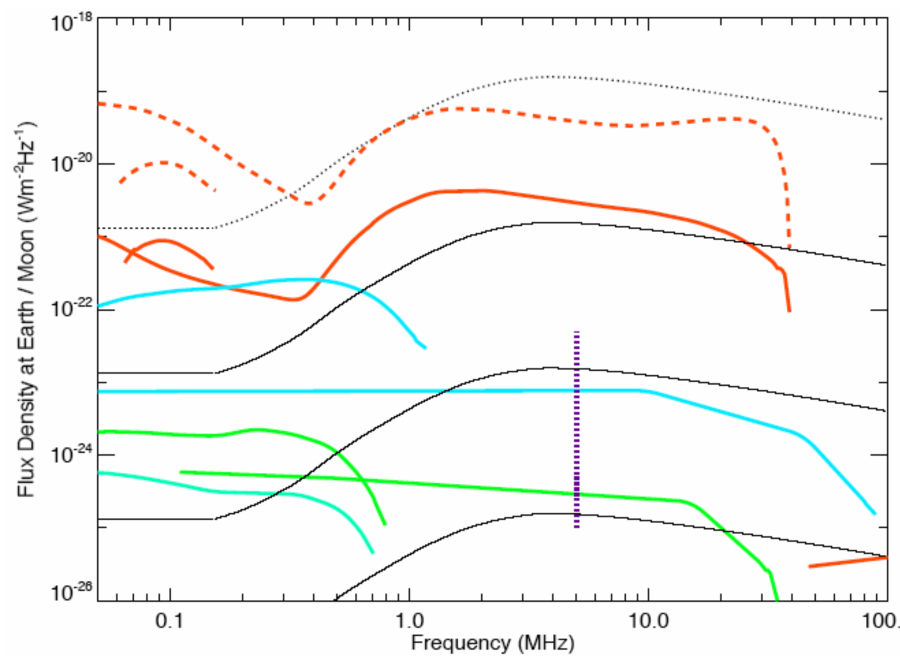


Planetary Radio Emission: New Phenomena at VLF

- Coherent Planetary Cylcotron-Maser Emission
  - As strong or stronger than the sun
  - Direct measure of magnetic field
  - „Hot Jupiters“ may be 10^5 times brighter and detectable from the moon

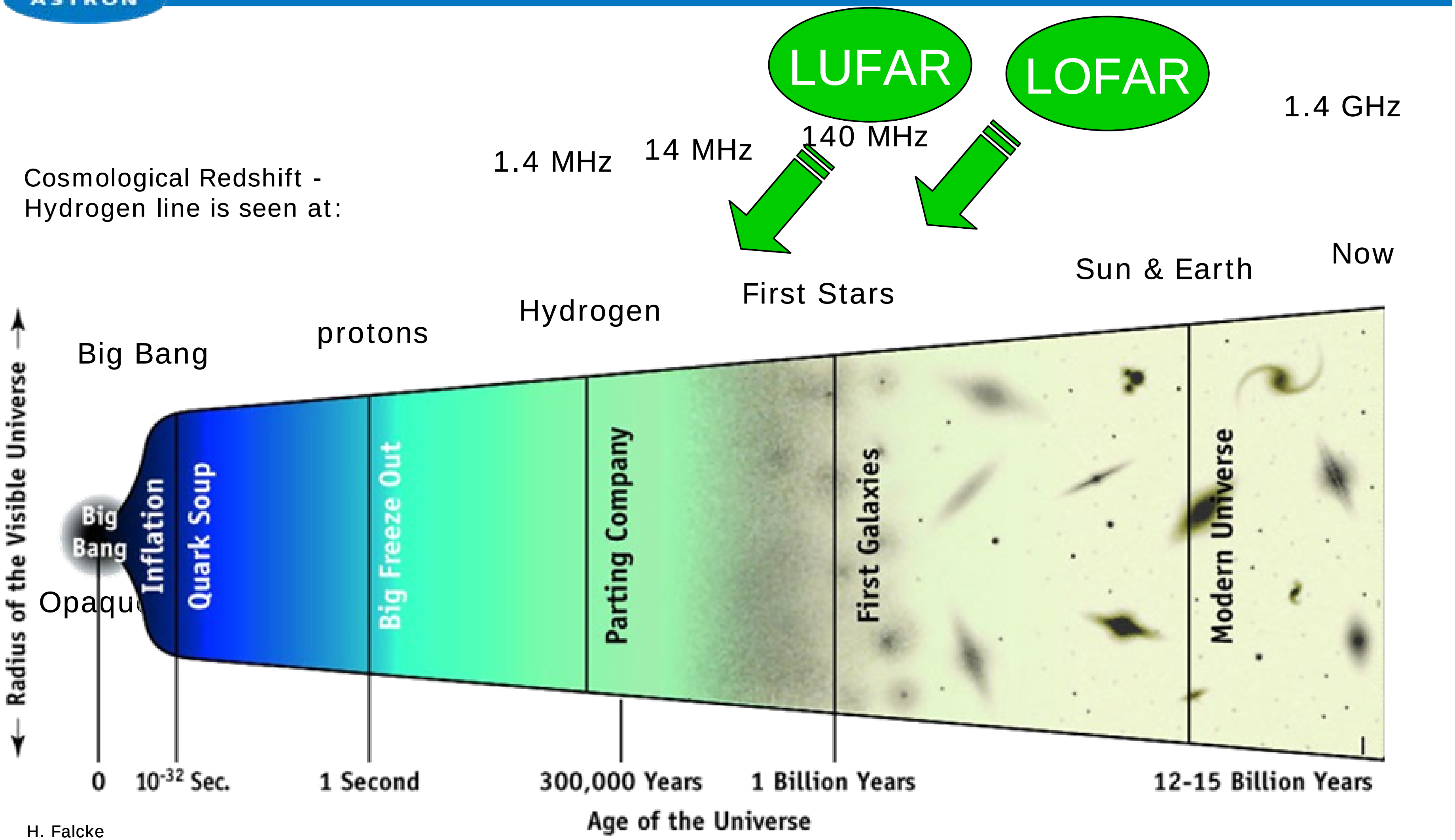
  ⇒ Very interesting for exoplanet search and study (Lazio et al. 2004)

- all Jovian emissions + Saturn auroral emissions
- + Uranus & Neptune auroral emissions
  + Saturn & Uranus lightning (including LF cutoff)



Zarka (2006)

Science at Long Wavelengths: Very Early Universe



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HI in the dark ages

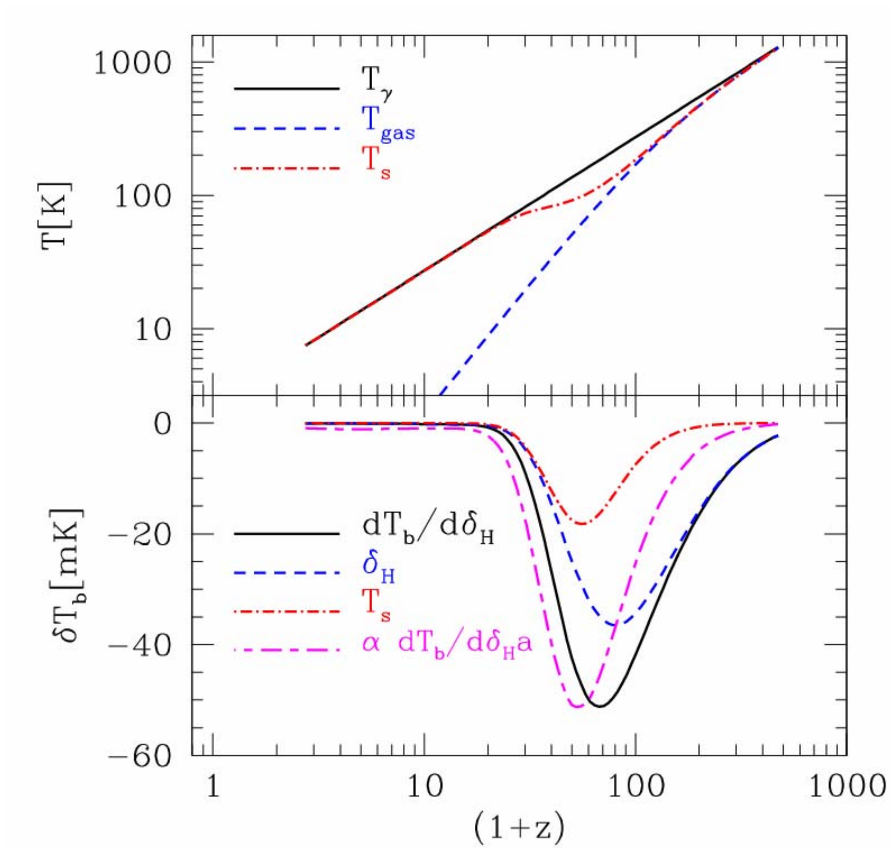
- The 21cm signal is simply shaped by gravity, adiabatic cosmic expansion, and well-known atomic physics ...
- ... and is not contaminated by complex astrophysical processes that affect the intergalactic medium at $z < 30$.

⇒ Allows clean 3D tomographic view of cosmic evolution.

⇒ Extremely difficult observation and calibration (req.: SNR>1,000,000:1)

⇒ Needs perfect conditions & extensive prototyping

Decoupling of CMB, gas, and spin temperatures



Loeb & Zaldarriaga, Phys. Rev. Lett., 2004
Scott & Rees, MNRAS, 1990

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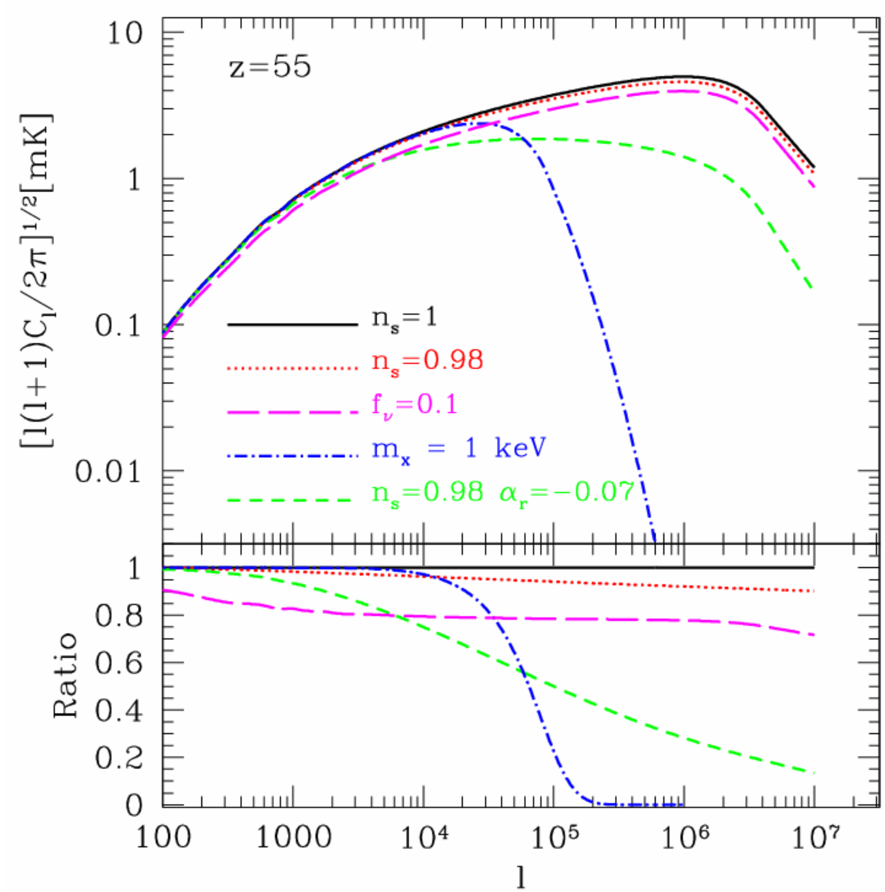
power spectrum for 21cm anisotropies at 25 MHz

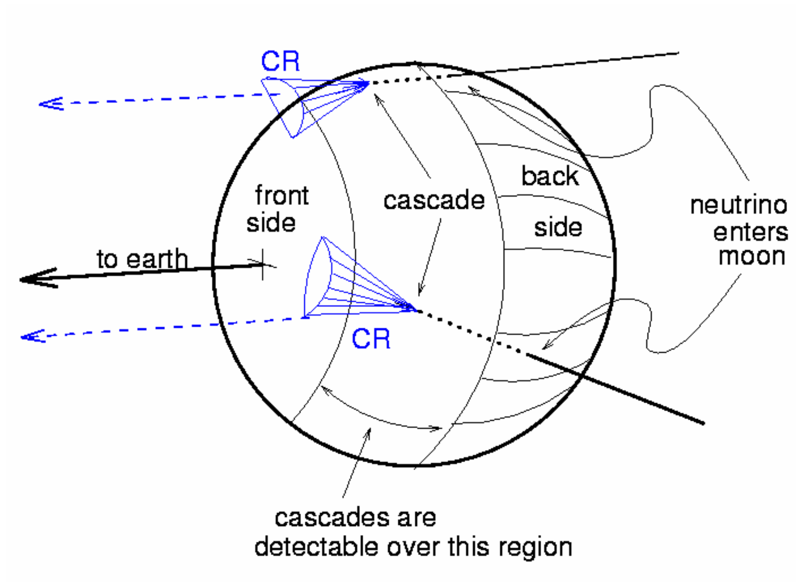


Loeb & Zaldarriaga, Phys. Rev. Lett., 2004
Scott & Rees, MNRAS, 1990

Ultra-High Energy Neutrino Detections

- Ultra-high energy particle showers hitting the moon produce radio Cherenkov emission (Zas, Gorham, ...).
- This provides the largest and cleanest particle detector available for direct detections at the very highest energies.
- In the forward direction (Cherenkov cone) the maximum of the emission is in the GHz range.
- Current Experiments:
  - ANITA
  - GLUE
  - FORTE
  - RICE

radio from
neutrinos hitting the moon

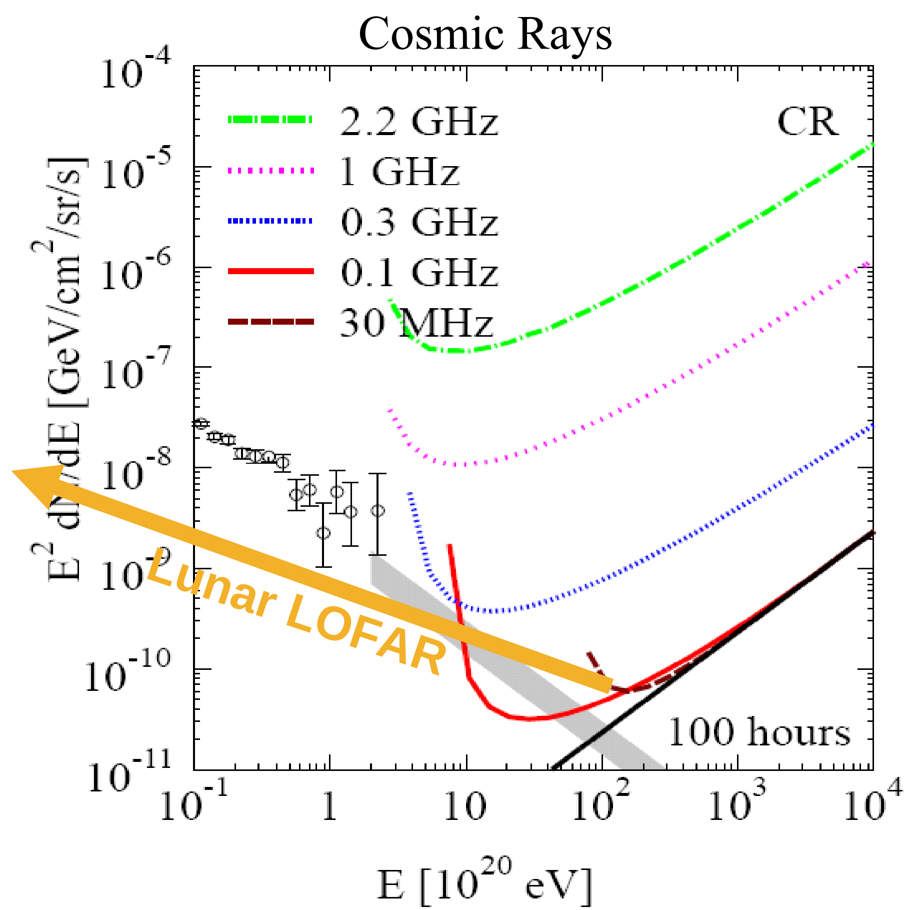


from Gorham et al. (2000)

Radio Observations of the Moon: Different Frequencies

- Low frequencies are more isotropic and penetrate moon deeper.
- LOFAR observations of the moon will give best limit on super GZK Cosmic Rays and Neutrinos!
- VLF antennas on the moon may give multi-km³ neutrino detector.

⇒ In-situ prototyping needed!



νMoon Collaboration: Scholten, Bacelar, Braun, de Bruyn. Falcke, Stappers, Strom 2006, Astropart Phys.

The finest achievable resolution element is ~λ/D.

Large radio waves require large telescopes!

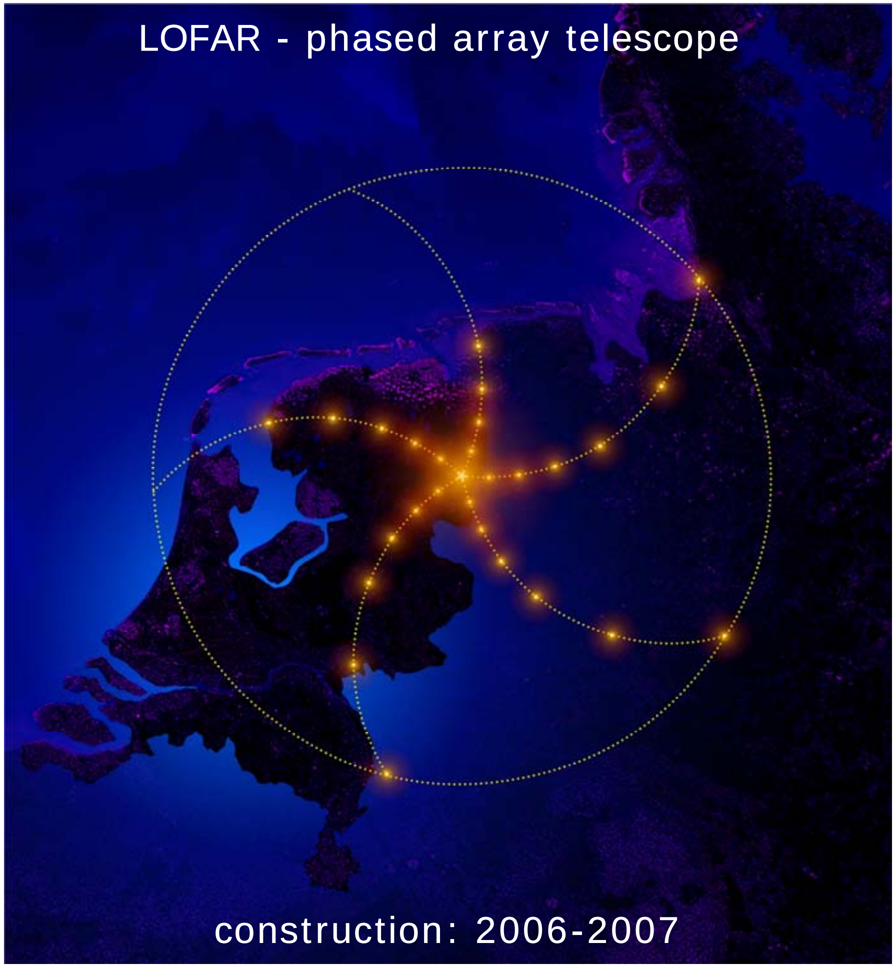
100 m Telescope Effelsberg/Germany

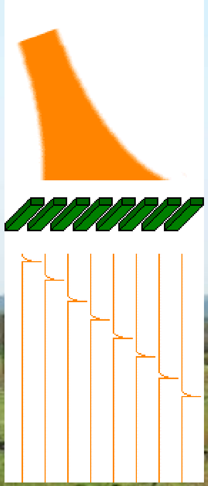
How do we get this (3200 t) ....

... to here?!

LOFAR – the next generation radio telescope

- Telescope the size of the Netherlands plus Germany.
- Pathfinder for the Square-Kilometer Array (SKA).
- Frequencies: 30 - 240 MHz
- Realized as a wide-area sensor network with ~14.000 cheap sensors: radio & geo sensors!
- Two orders of magnitude improvement in resolution and sensitivity
- Science applications: Big bang, astroparticles and the unknown.
- Current Funding: 74 M€
- German partner consortium formed, funding for first German station available





List for

R_{max} and ... ails about other fiel... on of the Fields"

DETAILS

EXPLANATION OF THE FIELDS

1-100 | 101-200 | 201-300 | 301-400 | 401-500

Rank	Site Country/Year	Computer / Processors Manufacturer	R_{max} R_{peak}
1	DOE/NNSA/LLNL United States/2005	BlueGene/L **eServer Blue Gene Solution** / 65536 IBM	136800 183500
2	IBM Thomas J. Watson Research Center United States/2005	BGW **eServer Blue Gene Solution** / 40960 IBM	91290 114688
3	NASA/Ames Research Center/NAS United States/2004	Columbia **SGI Altix 1.5 GHz, Voltaire Infiniband** / 10160 SGI	51870 60960
4	The Earth Simulator Center Japan/2002	**Earth-Simulator** / 5120 NEC	35860 40960
5	Barcelona Supercomputer	MareNostrum **JS20 Cluster, PPC 970, 2.2**	27910 42144
6	ASTRON/University Groningen Netherlands/2005	**eServer Blue Gene Solution** / 12288 IBM	27450 34406.4

Paradigm shift: from steel to silicon.

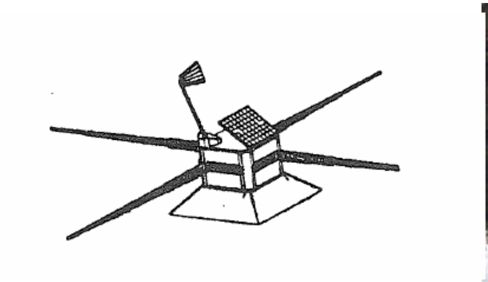
Past: a lot of steel to focus radiation on a single electronic receiver

Future: many digital receivers and massive data processing synthesize virtual telescope in software

LOFAR Lo-Band Antenna (30-80 MHz)

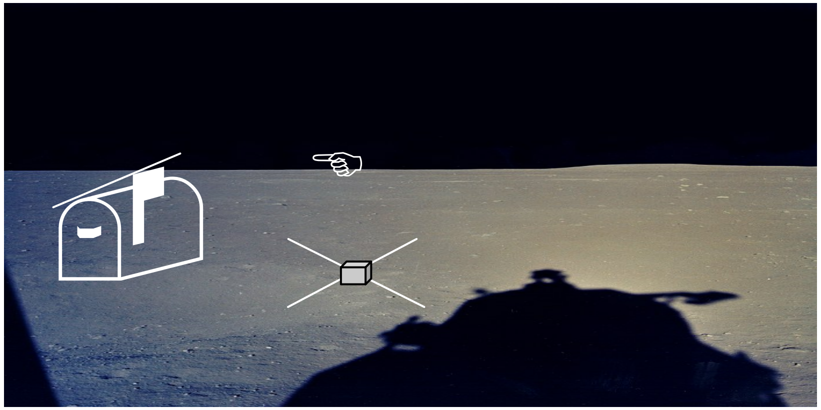
Lunar LOFAR: Distributed array of radio sensors

- Frequency range: 0-30 MHz, optimized for 1-10 MHz
- Antenna element: full-polarization short tripole antennas
- Tripole length: 7.5 m ($\lambda/4$, resonant at 10 MHz)
- explore very short, tripole "balls" $\Rightarrow$ need lot of power
- Installation:
  - Short baselines (1km) and short tripoles:
    - javelin launcher.
    - Power supply through cable
  - Long Baselines (10-100 km), long crossed dipoles:
    - Rover
    - Self-sufficient antennas
    - Flat on ground



crossed dipole

LOIS tripole antennas



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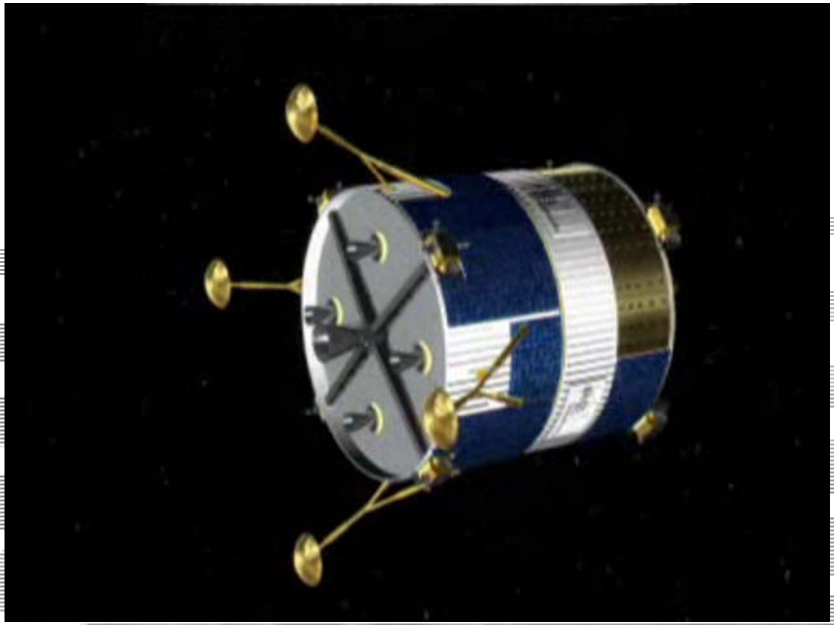

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Lunar LOFAR Scientific Topics

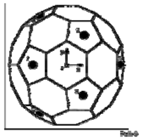
	Min # of Dipoles	Frequency	Baseline
Global EOR	1	1-100 MHz	0
Solar System	4-10	0-10 MHz	0.1-1 km
Local Bubble 3D-Tomography	10-100	0.1-3 MHz	30-1000 km
Extragalactic Surveys	10-100	3-30 MHz	1-100 km
Neutrinos	10-100	1-100 MHz	10 km
Exoplanets	100-1000	0.1-10 MHz	1-10 km
Dark Ages	1000-10000	1-80 MHz	1-10 km

Lunar LOFAR as a pathfinder for other observatories

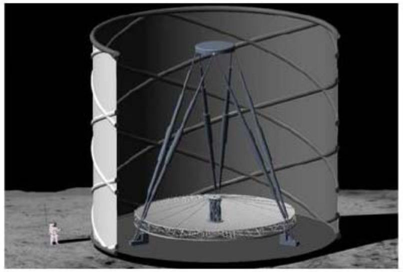
- A Lunar LOFAR would provide the first infrastructure for astronomy on another “planet”.
- This may open the door for other observatories making use of “exploration” efforts:
  - small robotic optical telescopes
  - X-ray, UV, submm telescopes
  - Large (~20m) liquid mirror infrared telescope
  - Gravity wave detectors, CR detectors?
  - “geo”-phones for study of lunar interior and neutrino detection

robotic telescopes

“geo”-phones



GW & CR sensors on the moon



Large IR telescope

Conclusion

- A VLF radio array can open up the last unexplored wavelength range in astronomy.
- The moon is unquestionably the very best site for a VLF array: large stable ground, no ionosphere, shielding from Earth+Sun interference (unique!)
- Science topics:
  - Solar System, Local Bubble, (Exo)-Planets+Transients, Surveys, Astroparticle Physics, Dark Ages
- Combine distributed antenna boxes with other "payloads": seismic sensor network, X-ray Antenna box, …