How to get light from the dark ages

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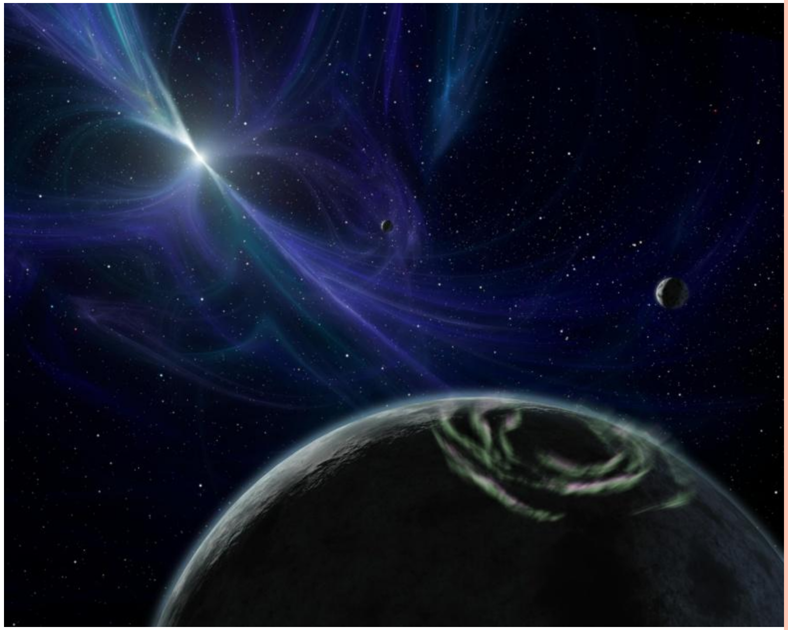
Outline

- Basics of Radio Astronomy
- Why go to the moon?
- What should we find there?

Basics of Radio Astronomy

Blackbody Radiation:

$$B = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



Rayleigh-Jeans Approximation:

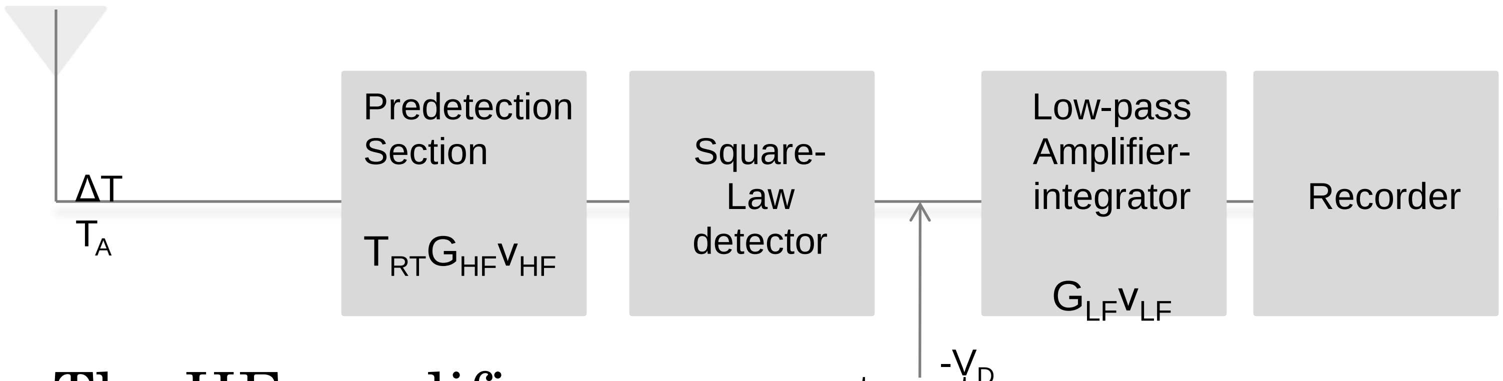
$$h\nu << kT$$

$$e^{\frac{h\nu}{kT}} - 1 = 1 + \frac{h\nu}{kT} - 1 = \frac{h\nu}{kT}$$

Thus the blackbody function becomes:

$$B = \frac{2kT}{\lambda^2}$$

- For a total power receiver:



- The HF amplifier power output:

$$W_{HF} = G_{HF}(T_{sys} + \Delta T)\Delta\nu_{HF}$$

- The detector has an output voltage that varies with input voltage squared. This means that the detector d-c output voltage is directly proportional to the input power or:

$$V_D + \Delta V = \beta G_{HF} k T_{sys} \Delta\nu_{HF} + \beta G_{HF} k \Delta T \Delta\nu_{HF}$$

- Because $\Delta V << V_{D \text{ i.e.}}$ $\Delta T << T_{sys}$ high amplification of ΔV is needed to get a reading on the recorder. To make this easier an external voltage of $-V_D$ is introduced leaving ΔV as the signal output voltage. Thus the signal power becomes:

$$W' = C'(k\Delta T\Delta \nu_{HF})^2$$

- A detector output voltage also exists generating a power density of:

$$W_{LF} = G_{LF} 2C'(kT_{sys})^2 \Delta\nu_{HF}\Delta\nu_{LF}$$

- The corresponding noise from ΔT is:

$$W' = G_{LF} C'(k\Delta T\Delta\nu_{HF})^2$$

- $\Delta T_{min} = T_{rms}$ the minimum detectable signal is defined to be the ΔT which produces a power equal to the noise output power W_{LF}. Thus setting the equations equal:

$$\Delta T_{\min} = T_{sys}\sqrt{\frac{2\Delta\nu_{LF}}{\Delta\nu_{HF}}}$$

- Given that

$$\Delta\nu_{HF} = \frac{\left[\int_0^\infty G_{HF}(\nu)d\nu\right]^2}{\int_0^\infty [G_{HF}(\nu)]^2 d\nu} \qquad \Delta\nu_{LF} = \frac{\int_0^\infty G_{LF}(\nu)d\nu}{G_{LF}(0)}$$

- And the gain function of an ideal integrator:

$$G(\nu) = \frac{\sin^2(0.5\omega t_{LF})}{(0.5\omega t_{LF})^2}$$

- Thus $\Delta v_{LF}=0.5/t_{LF}$

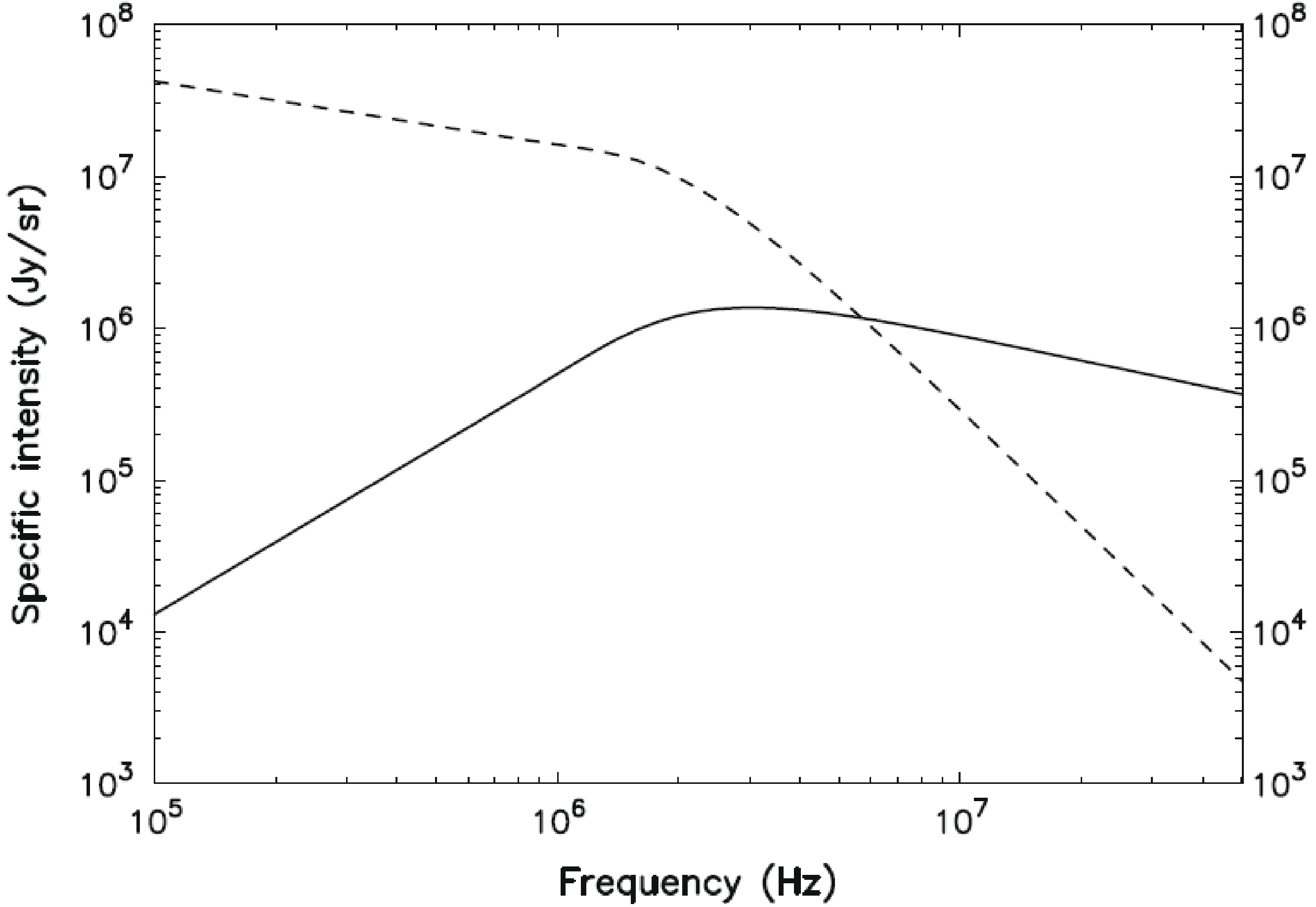
- Combining this with the T_{min} and altering the equation slightly for a dipole array yields:

$$T_{rms} = \frac{KT_{sys}}{\sqrt{\Delta \nu_{HF} t_{LF} N(N-1)}}$$

- And then substituting in the Rayleigh-Jeans Approximation:

$$B_{\min} = \frac{2kKT_{sys}}{\lambda^2 \sqrt{\Delta \nu t N(N-1)}}$$

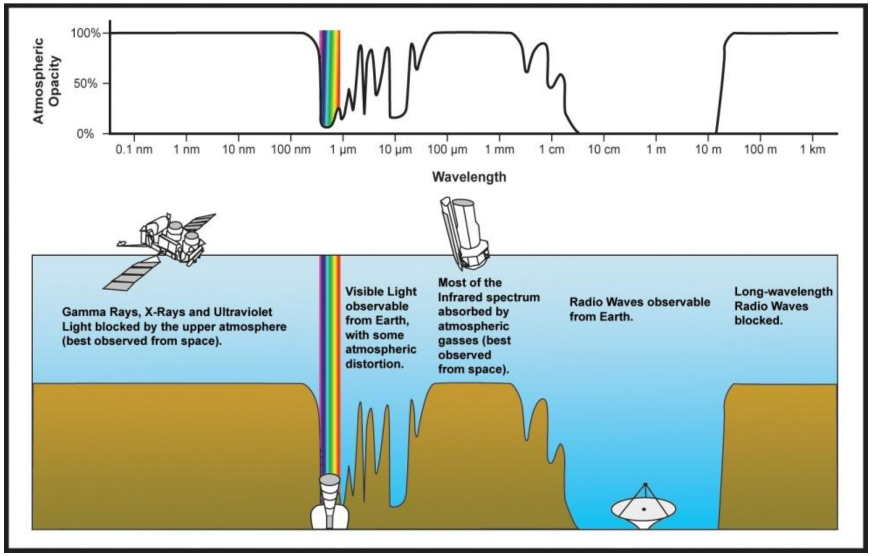
- Earlier we assumed that the T_{rms} was much less than the system temperature. In the Very Long Wavelength VLW this is true because the system temperature is dominated not by the mechanics but by the sky temperature.



Why Go To The Moon?

What's Wrong With The Earth?

- The same effect creating the high sky temperatures also occurs in Earth's ionosphere to a much greater degree.



- Beyond 30MHz, the plasma frequency of the ionosphere kicks in and the atmosphere becomes opaque

- Worse than that, fluctuations in the electron density lead to high magnitude scintillations all the way up to the 300MHz range.
- The moon does have an ionosphere of electrons but its much less dense than that of the Earth producing a lower plasma frequency and thus a lower cutoff.

$$\nu \approx \sqrt{n_e}$$

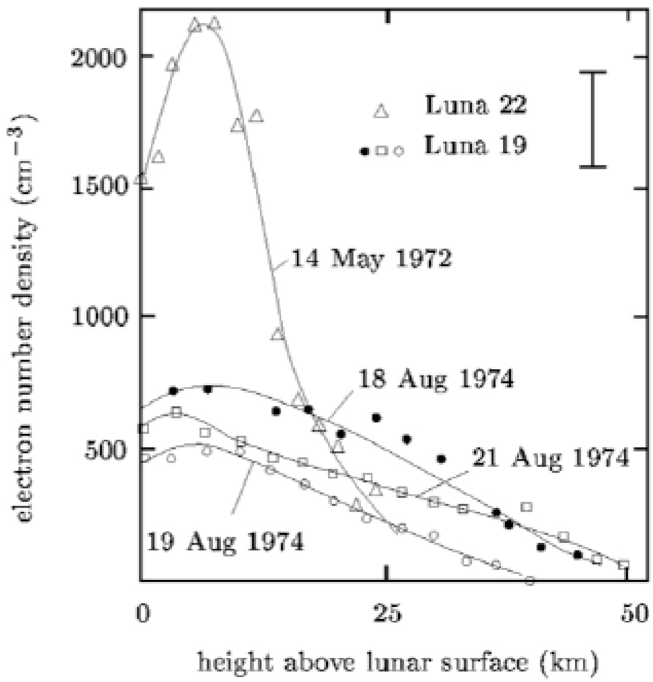
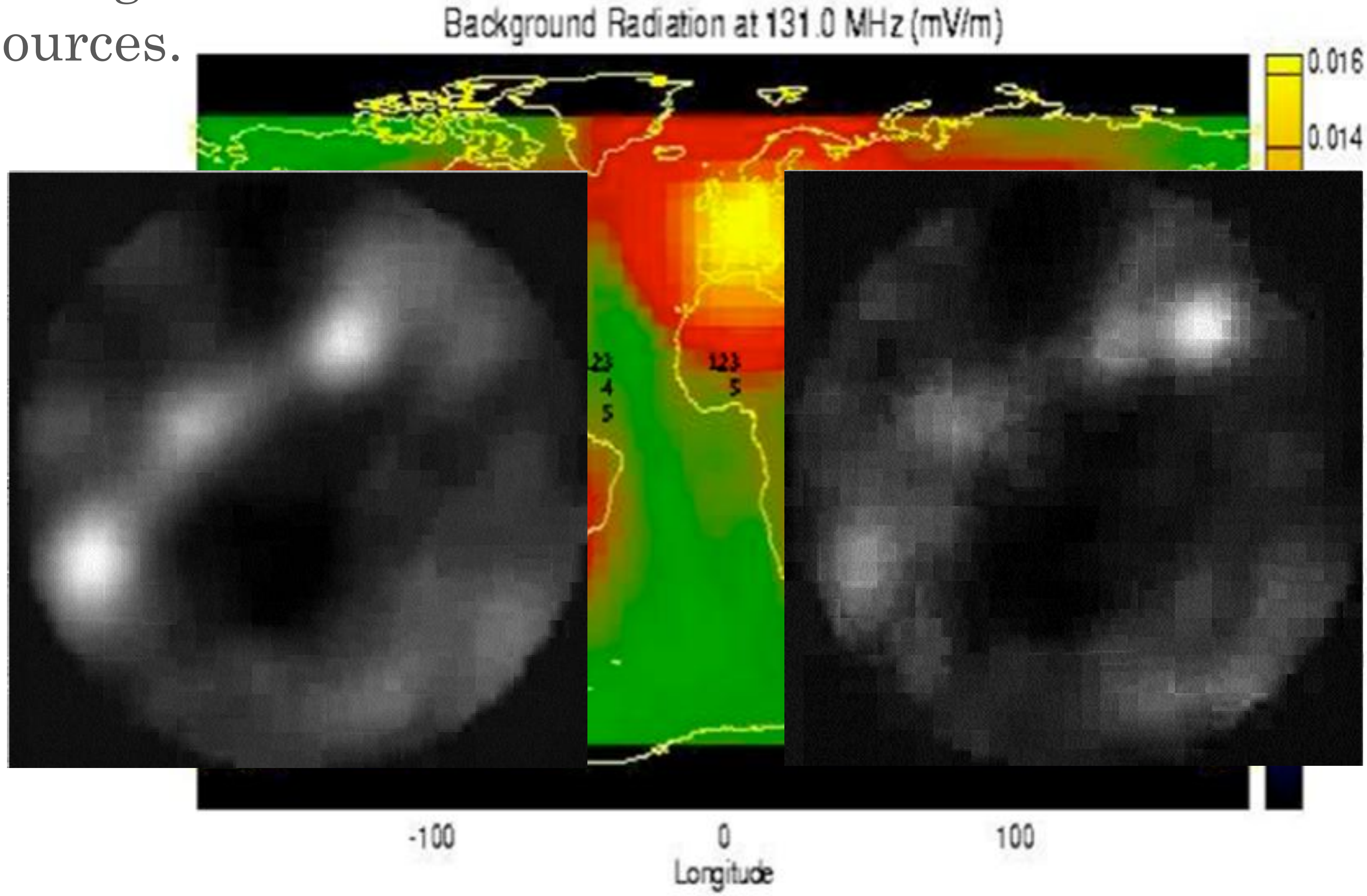


Figure 1. Lunar ionosphere electron densities derived from dual-frequency radio occultation measurements during the Luna 19 and Luna 22 missions (Vyshlov 1976; Vyshlov & Savich 1978).

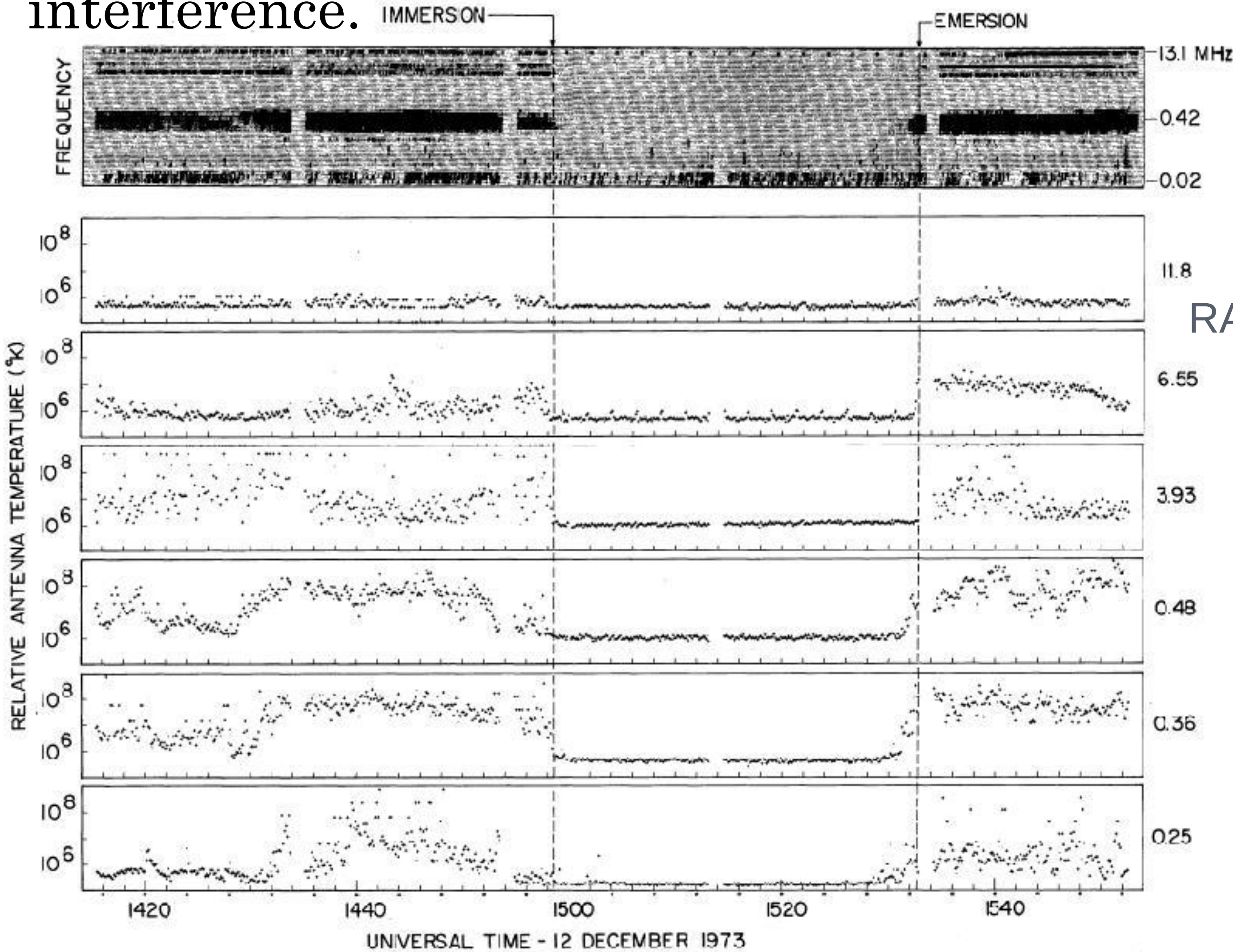
Radio Frequency Interference (RFI)

- One of the biggest problems in radio astronomy is telling the difference in local and astronomical sources.



FORTES satellite

- The lunar far side always faces away from the Earth creating a dead zone with much less interference.



RAE-2 1973

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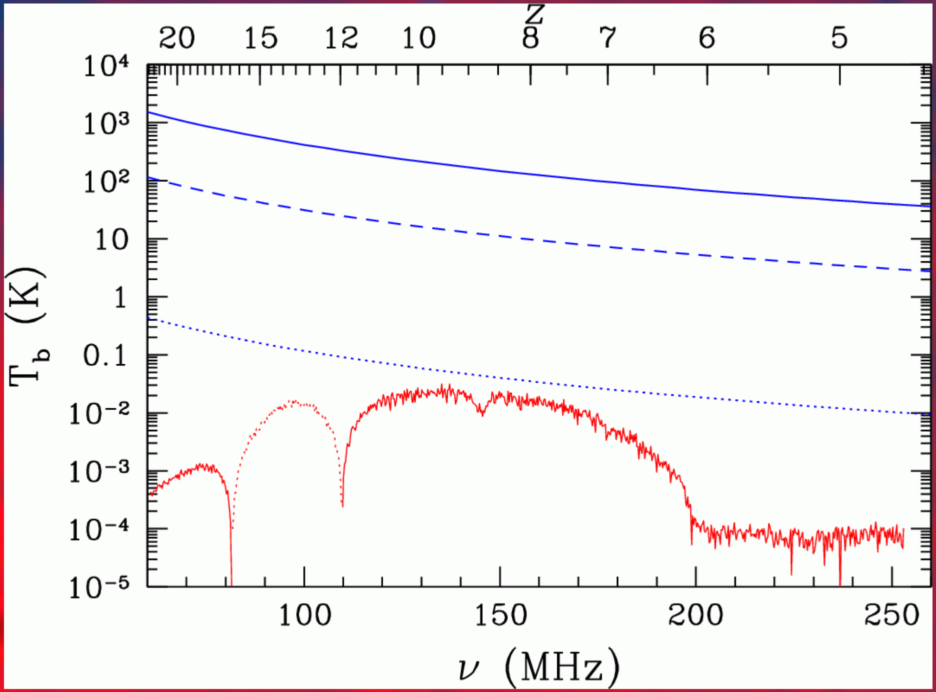
Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur 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

Galactic Synchrotron Emission

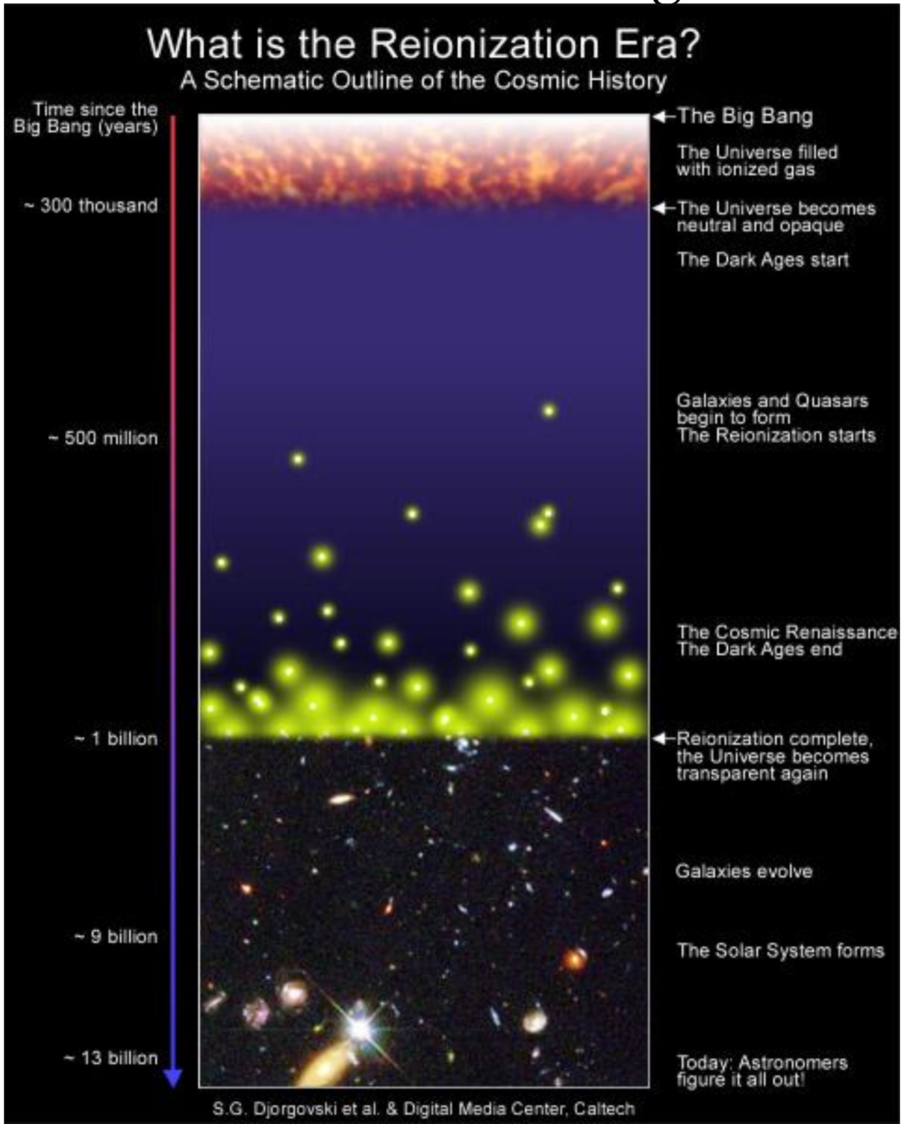
- A lunar array may eliminate RFI and lower the plasma frequency but it doesn't eliminate synchrotron emission which is 10^6 times brighter than the modeled 21-cm line.



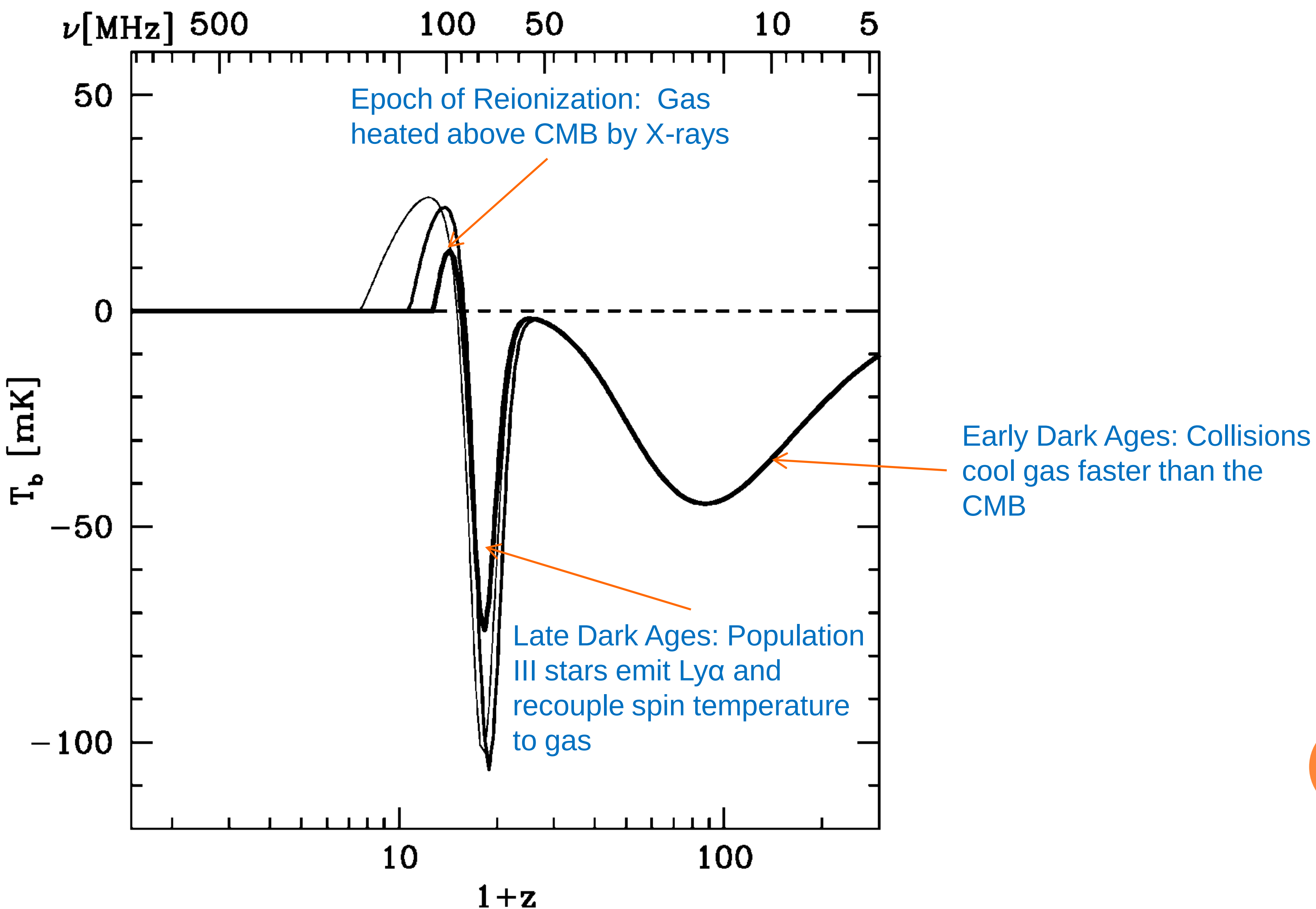
- Despite this hurdle, it should be noted that astronomers working on the CMB get a signal out of the same amount of noise.

Cosmology

- After the big bang at ~z=1000 the universe cooled and entered the cosmic dark ages.



- Finding the 21 cm line both at the epoch of reionization and during the dark ages will help constrain cosmological models.



- Given that the signal is expected to be redshifted to less than 100MHz it would be nearly impossible to find on the Earth but a single lunar dipole could find the Cosmic Dark Ages signal in 40 days.

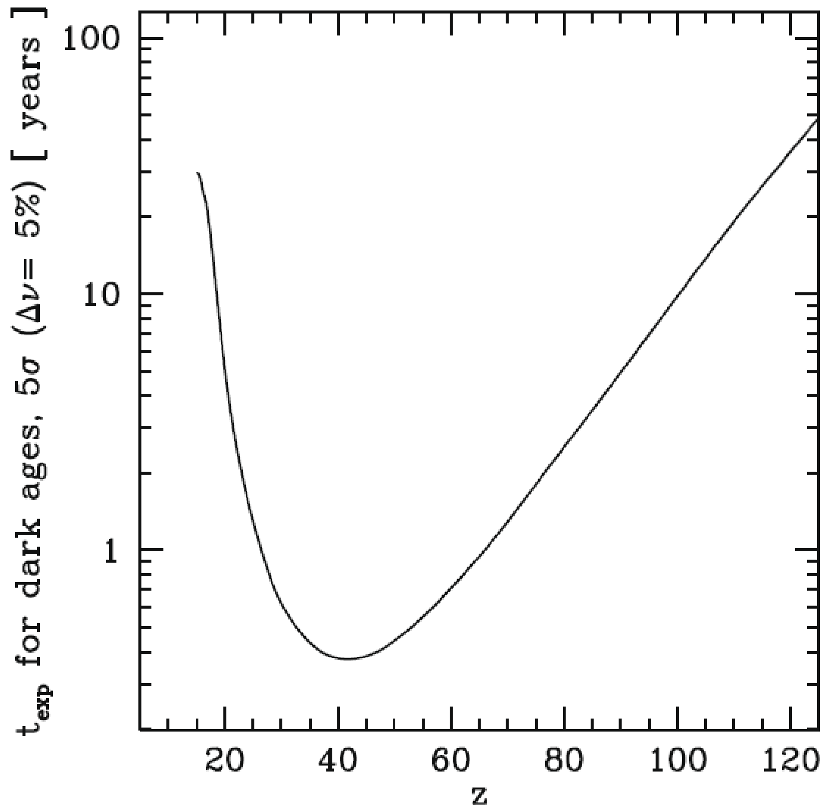


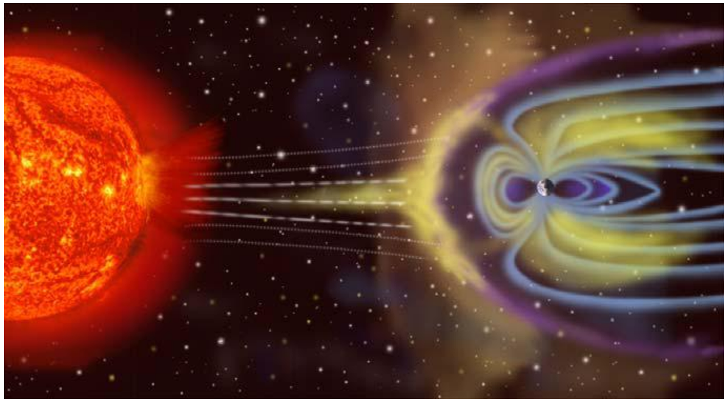
Fig. 10. Global 21-cm signal from HI in the dark ages. The plot shows the observing time needed to reach a 5-σ detection at 5% fractional bandwidth with a single dipole, as function of redshift. If N dipoles are added incoherently, then the observing time is reduced by a factor $\sqrt{N}$.

Dark Matter Decay Detection

- Another wonderful thing about the dark ages is the simplicity of the universe.
- This allows a unique chance to look for exotic heat signatures since without stars to provide heat even very small sources could be discovered
- One possible source that astronomers are on the lookout for is dark matter decay. As the dark matter decays it should heat the gas and alter the profile of the 21-cm line in a measureable way.

Extrasolar Planet Detection

- Planets with large magnetic fields bend the particles of the local solar wind generating electron cyclotron masers



- Information from the magnetic field's signature can constrain information on the planet's composition, rotation period, number of satellites, and habitability.

Other Areas of Research

- Surveying for Radio galaxies and quasars that are very bright at long wavelengths
  - Discovering high redshift sources
  - Pinning down the age of quasars and galaxies with jets
  - Constraining galaxy cluster formation models
- Identifying the structure of the ISM
  - Analyze the properties of the Warm Interstellar Medium
  - Mapping electron densities to find the source of cosmic rays
- Ultra high energy cosmic rays
  - Detection of hadronic cosmic rays
  - Detection of neutrinos
  - Detection of meteoritic impacts

Overview of science cases and requirements.

Topic	Our Sections	*Requirements*					
		Frequency/MHz	Resolution ϑ	Baselines/km	Expected signal[a]	N(Antennas)	t_{exp} (5-σ)
Cosmology	3.1						
Global Epoch of Reionization[b]	3.1.1	50–150	2π sr	0	5–50 mK	1	2 h–20 d
Global dark-ages signal	3.1.2	30–45	2π sr	0	0–40 mK	1 or more	0.3–30 year
EoR tomography	3.1.3	50–150	$\approx 10' - 1'$	0.7–20	$\approx$ 1 mK	$10^5 - 10^7$[c]	year
EoR 21-cm power spectrum	3.1.4	50–150	$\approx 2^\circ - 2'$	0.05–10	$\approx$0.3–5 mK	$10^3 - 10^5$[c]	year
Dark-ages 21-cm power spectrum	3.1.4	30–45	$\approx 20' - 2'$	1–20	$\approx$0.03–1 mK	$10^4 - 10^8$[c]	year
Extragalactic surveys	3.2	10	$1'$	0.1–100	$\approx$ 65 mJy[d]	300	2 year
Galactic surveys	3.3						
Solar System neighbourhood	3.3.1	0.1–10	degrees	0.3–30	10,000 K	10–100	year
Origin of cosmic rays	3.3.2	0.1–30	$1''$	$(3-30) \times 10^3$[e]	155,000 K	100,000	100 d
Transients	3.4						
Solar and planetary bursts	3.4.1	0.1–30	degrees	0.5–200	MJy	1–100	min–h
Extrasolar planets	3.4.2	0.5–30	$\lesssim 1'$	$\gtrsim 35-1000$	1–10 mJy	$10^4 - 10^5$[f]	15 min
Ultra-High Energy particles	3.5	10–100	N/A[g]	0–5	100 MJy	1–100	N/A (bursts)[h]
Meteoritic Impacts	3.6						

Necessary Stepping Stones

I. Start with a pathfinder mission with a single antenna. This should be able to measure the effects of the moon's ionosphere, the electrical properties of the surface, confirm the RFI environment and detect the redshift of the EoR.

II. Send a two element interferometer to prove lunar interferometry and do a simple sky survey.

III. Send a three element telescope to look for high energy particles.

IV. Build a 30-300 element telescope over 30-100km to look for ISM tomography, planetary bursts, and to do extragalactic surveys.

V. Construct the full 10^3 -10^7 element telescope over tens of kilometers to finally investigate the cosmic dark ages and measure the magnetic bursts of extrasolar planets.

Open Questions

- How does the moon's ionosphere vary?
- What are the electrical properties of the lunar surface?
- What effects do meteoritic impacts have on measurements?
- How does the optical depth of the ISM vary?
- How much scattering do the IPM and ISM do at frequencies?


Questions?

References

- Jester S. and Falke, H. (2009) "Science with a lunar low-frequency array: From the dark ages of the Universe to nearby exoplanets." *New Astronomy Reviews*, *53*, 1-26.
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