Peering through the "Dark Ages" with a Low Frequency Telescope on the Moon

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(with contributions from A. Loeb,
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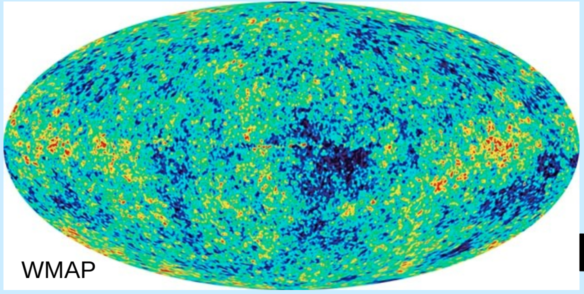
Presentation to the *Committee on the Scientific Context for the Exploration of the Moon* –
February 15, 2007

From the CMB **400,00 yrs after Big Bang**



WMAP

To

Clusters Of Galaxies

Today

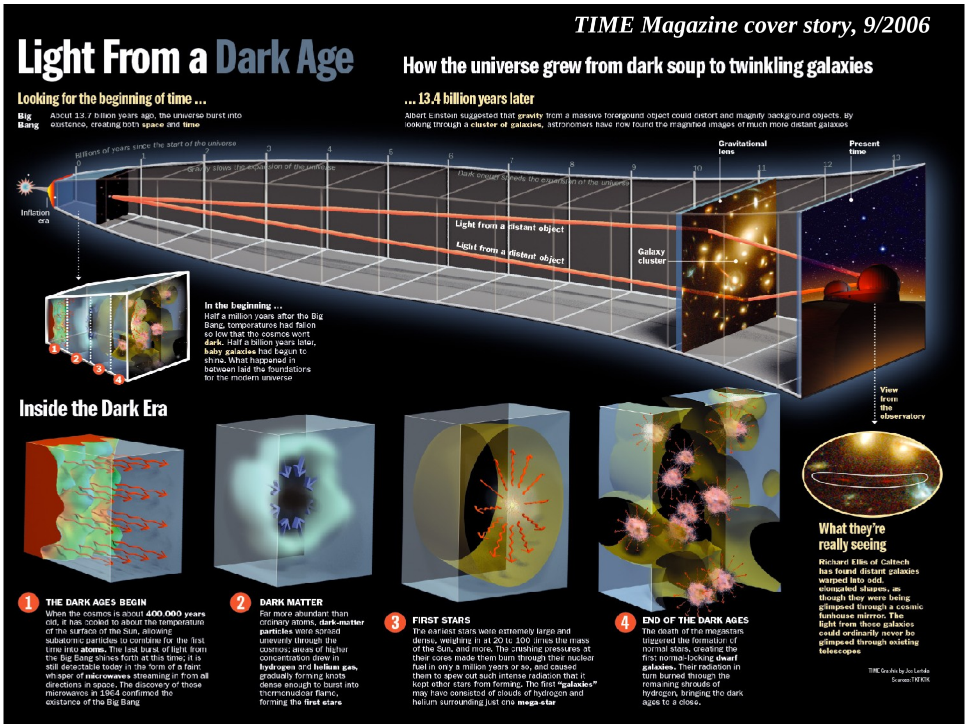
HST

The Universe In Transition

Recombination (400,000 yrs)

The Dark Ages

Reionization & 1st stars (10^8 yrs)



TIME Magazine cover story, 9/2006

Light From a Dark Age

How the universe grew from dark soup to twinkling galaxies

Looking for the beginning of time ...

Big Bang About 13.7 billion years ago, the universe burst into existence, creating both **space** and **time**

... 13.4 billion years later

Albert Einstein suggested that **gravity** from a massive forergound object could distort and magnify background objects. By looking through a **cluster of galaxies,** astronomers have now found the magnified images of much more distant galaxies

In the beginning ...
Half a million years after the Big Bang, temperatures had fallen so low that the cosmos went **dark.** Half a billion years later, **baby galaxies** had begun to shine. What happened in between laid the foundations for the modern universe

Inside the Dark Era

① **THE DARK AGES BEGIN**
When the cosmos is about **400,000 years** old, it has cooled to about the temperature of the surface of the Sun, allowing subatomic particles to combine for the first time into **atoms.** The last burst of light from the Big Bang shines forth at this time; it is still detectable today in the form of a faint whisper of **microwaves** streaming in from all directions in space. The discovery of those microwaves in 1964 confirmed the existence of the Big Bang

② **DARK MATTER**
Far more abundant than ordinary atoms, **dark-matter particles** were spread unevenly through the cosmos; areas of higher concentration drew in **hydrogen** and **helium gas,** gradually forming knots dense enough to burst into thermonuclear flame, forming the **first stars**

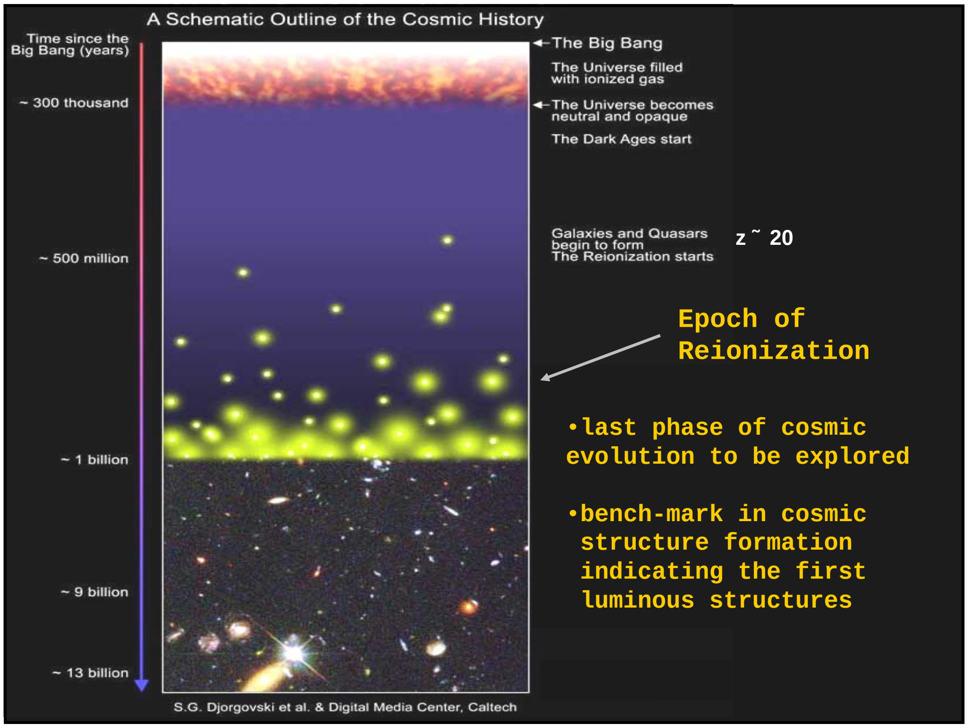
③ **FIRST STARS**
The earliest stars were extremely large and dense, weighing in at 20 to 100 times the mass of the Sun, and more. The crushing pressures at their cores made them burn through their nuclear fuel in only a million years or so, and caused them to spew out such intense radiation that it kept other stars from forming. The first **"galaxies"** may have consisted of clouds of hydrogen and helium surrounding just one **mega-star**

④ **END OF THE DARK AGES**
The death of the megastars triggered the formation of normal stars, creating the first normal-looking **dwarf galaxies.** Their radiation in turn burned through the remaining shrouds of hydrogen, bringing the dark ages to a close.

What they're really seeing

Richard Ellis of Caltech has found distant galaxies warped into odd, elongated shapes, as though they were being glimpsed through a cosmic funhouse mirrror. The light from these galaxies could ordinarily never be glimpsed through existing telescopes

TIME Graphic by Joe Lertola
Sources: TKTKTK



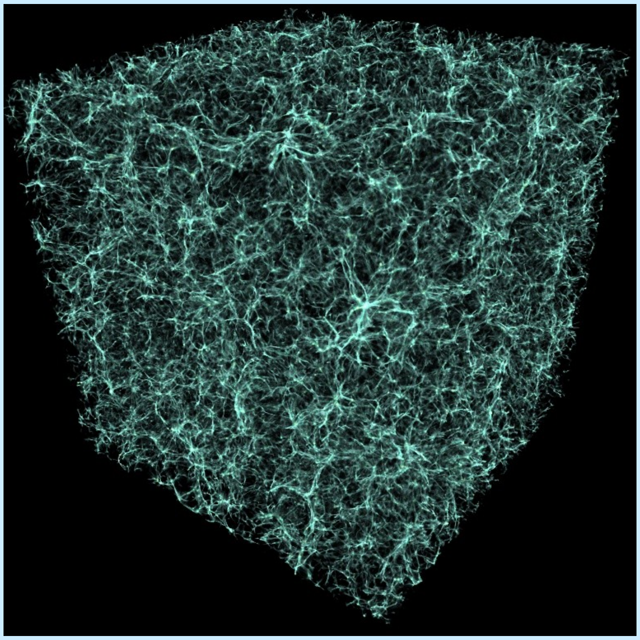
A Schematic Outline of the Cosmic History

z ˜ 20

S.G. Djorgovski et al. & Digital Media Center, Caltech

Epoch of Reionization

- last phase of cosmic evolution to be explored
- bench-mark in cosmic structure formation indicating the first luminous structures



Emergence of Baryonic Structure In The Universe

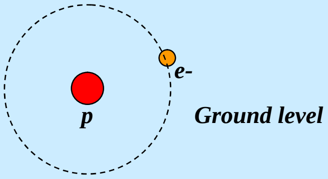
LCDM Hydo +
N-body Light Cone
Simulation using Enzo

E. Hallman & J. Burns
University of Colorado

B. O'Shea
Los Alamos National Lab

M. Norman
U. California – San Diego

Hydrogen

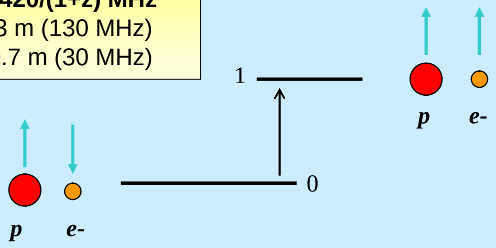


excitation rate= (atomic collisions)+(radiative coupling to CMB)

Couple T_S *to* T_k *Couples* T_S *to* $\mathbf{T_{CMB}}$

spin

21 (1+z) cm = 1420/(1+z) MHz
At z=10, λ = 2.3 m (130 MHz)
At z=50, λ = 10.7 m (30 MHz)

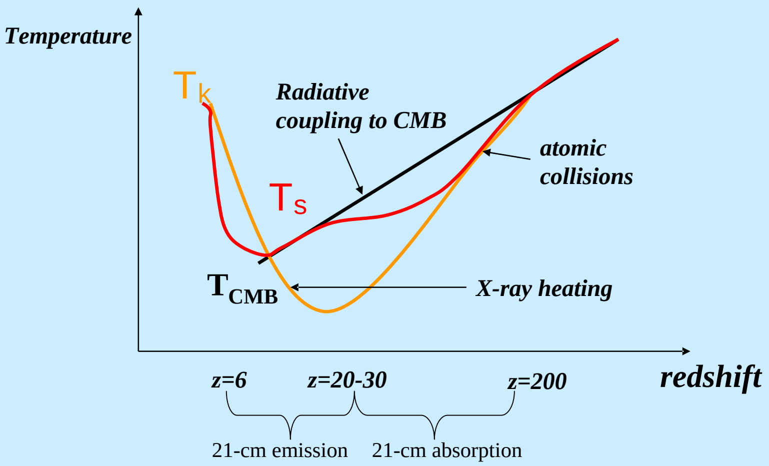


$\mathbf{n_1/n_0 = g_1/g_0 \exp(-T_*/T_s)}$ where $g_1/g_0=3$, $T_*=0.068$ K

Predicted by Van de Hulst in 1944; Observed by Ewen &Purcell in 1951 at Harvard

Thermal History

(adapted from Loeb, 2006, astro-ph/063360)



Sources of 21cm fluctuations

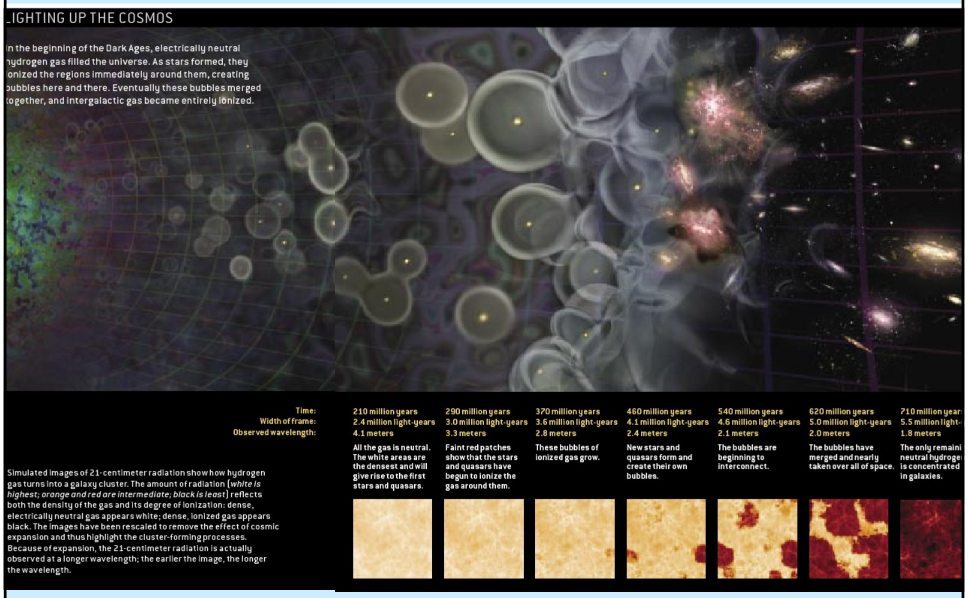
Density inhomogeneties (Loeb & Zaldarriaga 04) and peculiar velocities (Barkana & Loeb 04)

Ionized bubbles (Madau,Meiksin &Rees 1997;Furlanetto et al. 2004; Gnedin & Shaver 2003)

Emision from mini-halos (Iliev, Shapiro, et al. 2002)

Fluctuations in Lya flux, and gas temperature (Barkana & Loeb 2004)

A. Loeb, *Scientific American,* November 2006



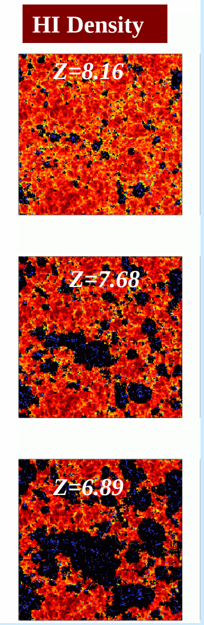
LIGHTING UP THE COSMOS

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Time:	210 million years	290 million years	370 million years	460 million years	540 million years	620 million years	710 million year
Width of frame:	2.4 million light-years	3.0 million light-years	3.6 million light-years	4.1 million light-years	4.6 million light-years	5.0 million light-years	5.5 million light-
Observed wavelength:	4.1 meters	3.3 meters	2.8 meters	2.4 meters	2.1 meters	2.0 meters	1.8 meters
	All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.	Faint red patches show that the stars and quasars have begun to ionize the gas around them.	These bubbles of ionized gas grow.	New stars and quasars form and create their own bubbles.	The bubbles are beginning to interconnect.	The bubbles have merged and nearly taken over all of space.	The only remaini neutral hydroge is concentrated in galaxies.

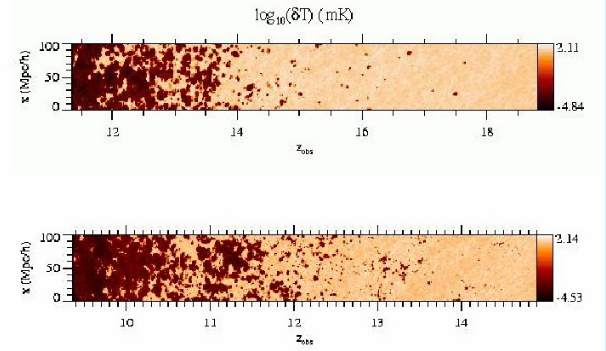
Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.

HI Density



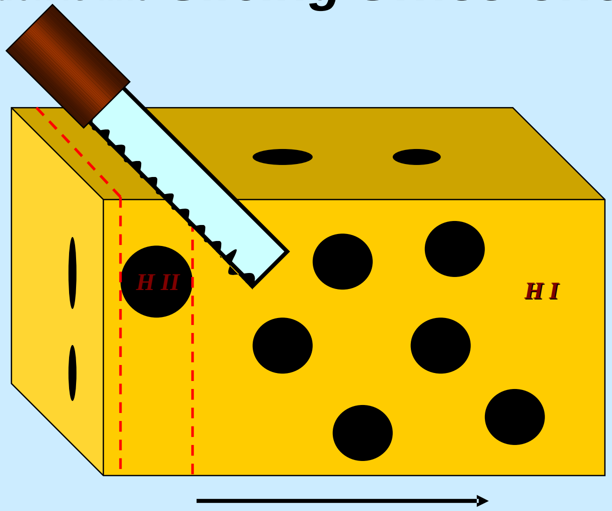
Zahn et al. 2006

21cm Brightness



Mellema et al. 2006

21cm Tomography of Ionized Bubbles During Reionization is like ***Slicing Swiss Cheese***



Observed wavelength ⇔ distance

21cm (1+z)

(Loeb, 2006, astro-ph/063360)

Experiments on the Ground

***MWA (Mileura Wide-Field Array)**
in Australia

MIT/ATNF/CfA (80-300 MHz)

LOFAR (Low-frequency Array)

Netherlands (30-80 MHz)

***21CMA (formerly known as** PAST)

China

PAPER

UCB/NRAO

GMRT (Giant Meterwave Radio Telescope)

India/CITA/Pittsburg

SKA (Square Kilometer Array)

International

Indian Giant Meterwave Radio Telescope

30 dishes @45m ea.

Operates in 2m band

Collaborators: Y. Gupta (chief scientist), Rajaram Nityananda (director), R. Subramanian (Raman)

GALFORD MEADOW –– NRAO: GREEN BANK, WV

D. Backer, A. Parsons, M. Wright, D. Werthimer (UC Berkeley),
R. Bradley, C. Parashare, N. Gigliucci, D. Boyd (NRAO, UVA)

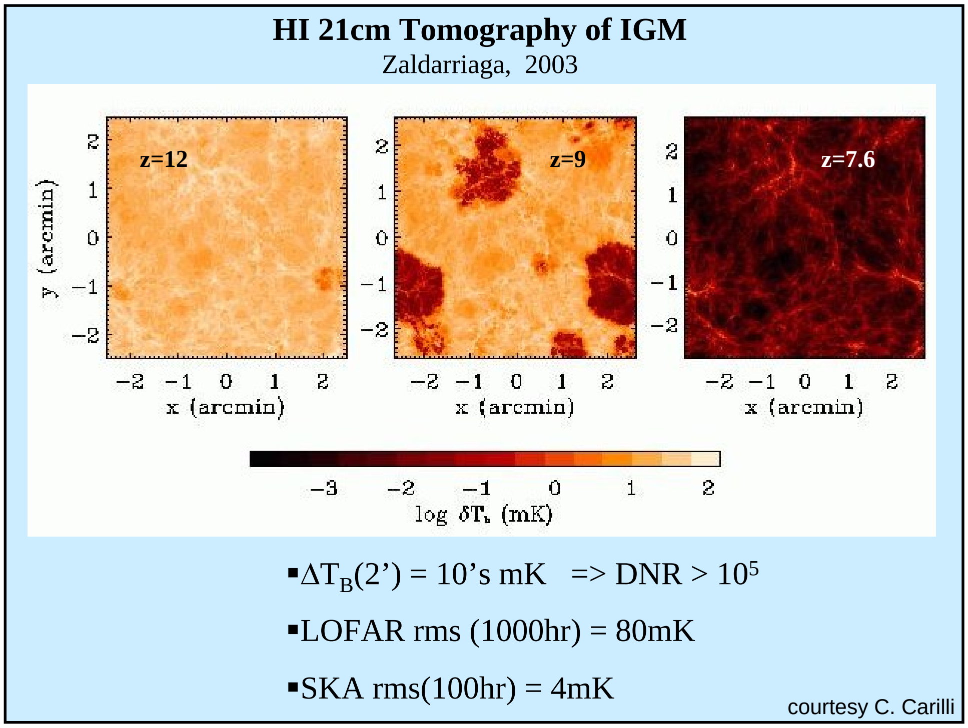
Mileura Wide-Field Array: *mapping cosmic hydrogen through its 21cm emission*

- 4mx4m tiles of 16 dipole antennae, 80-300MHz.
- 500 antenna tiles with total collecting area 8000 sq.m. at 150MHz across a 1.5km area; few arcmin resolution.

courtesy J. Hewitt

LOFAR Low-Band Antenna (30-80 MHz)

21-cm absorption of HI

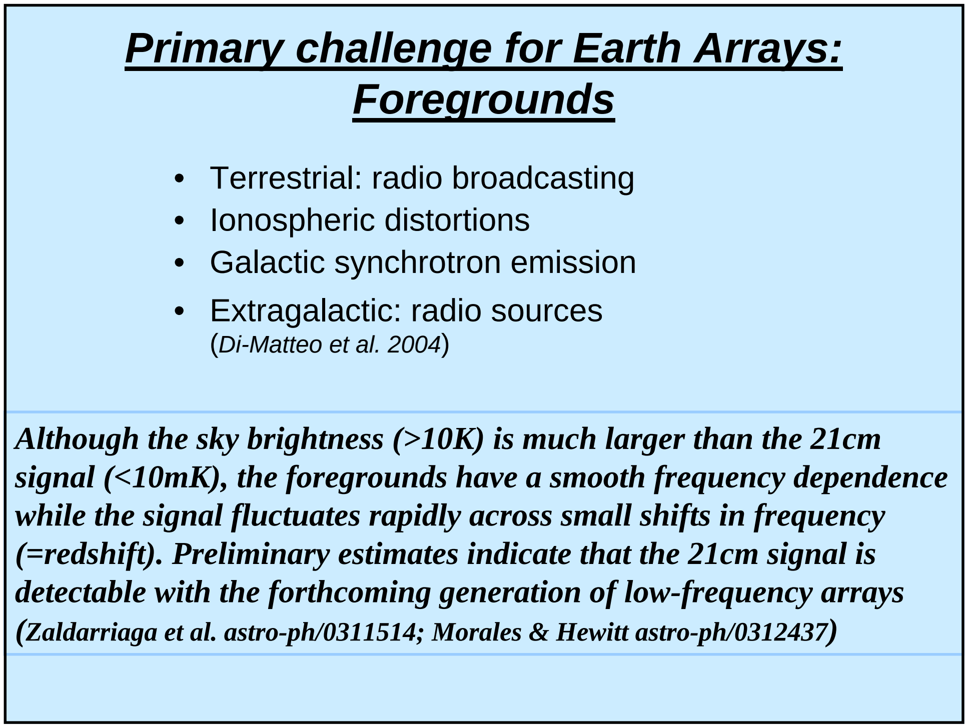


HI 21cm Tomography of IGM

Zaldarriaga, 2003

- $\Delta T_B(2') = 10$'s mK => DNR > 10^5
- LOFAR rms (1000hr) = 80mK
- SKA rms(100hr) = 4mK

courtesy C. Carilli



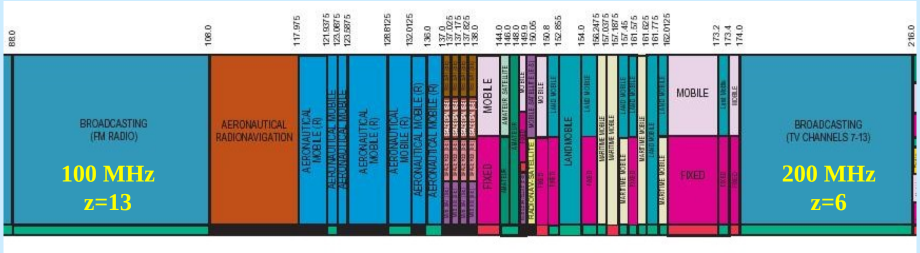
Primary challenge for Earth Arrays: Foregrounds

- Terrestrial: radio broadcasting
- Ionospheric distortions
- Galactic synchrotron emission
- Extragalactic: radio sources
  (*Di-Matteo et al. 2004*)

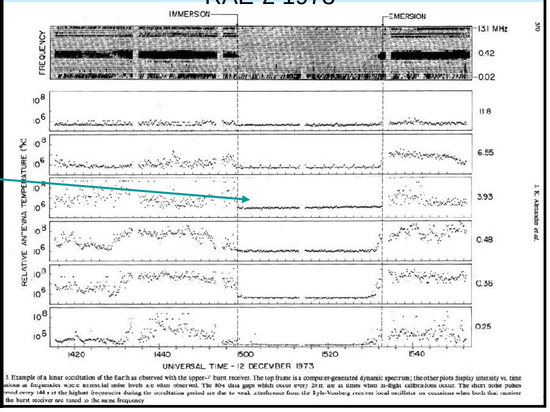
Although the sky brightness (>10K) is much larger than the 21cm signal (<10mK), the foregrounds have a smooth frequency dependence while the signal fluctuates rapidly across small shifts in frequency (=redshift). Preliminary estimates indicate that the 21cm signal is detectable with the forthcoming generation of low-frequency arrays (Zaldarriaga et al. astro-ph/0311514; Morales & Hewitt astro-ph/0312437)

Lunar Advantage I: Interference

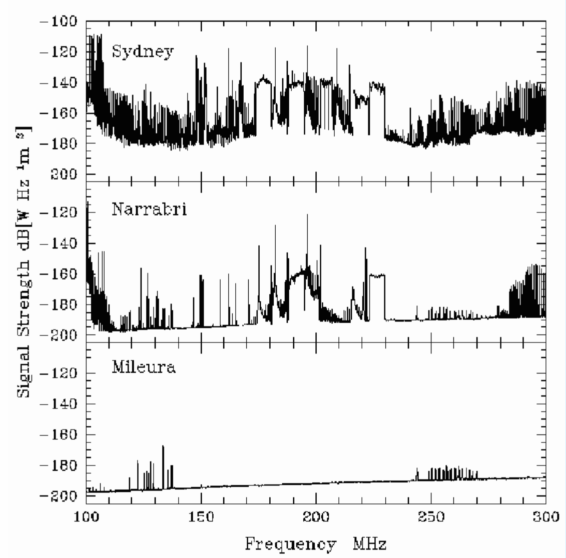
(courtesy C. Carilli, 2006)



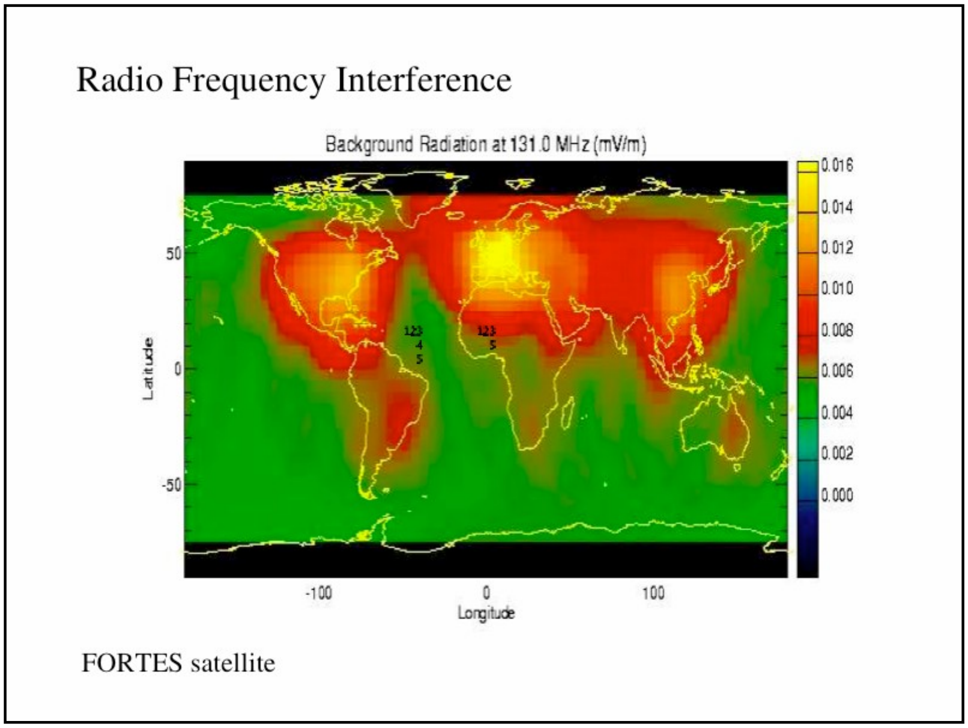
RAE-2 1973



Terrestrial Radio Frequency Interference

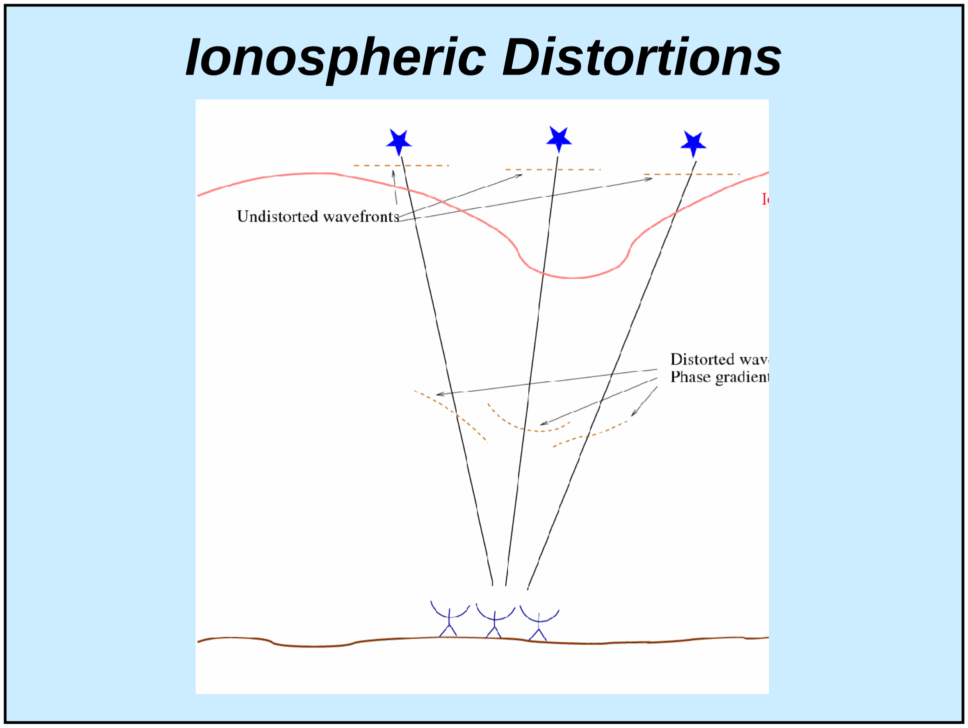


200dB = 10^6Jy ; ***Required:*** ~ 10µJy



Radio Frequency Interference

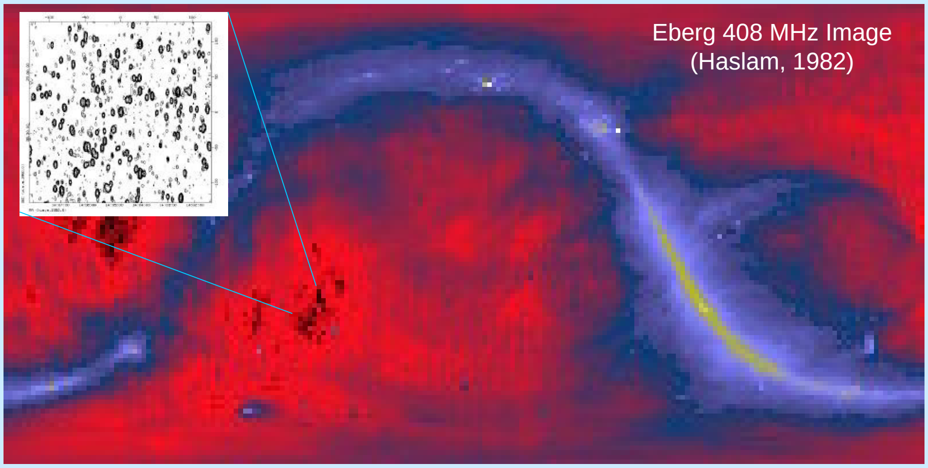
FORTES satellite



Ionospheric Distortions

Remaining challenge: Low frequency background

- Coldest regions: $T = 100 (\nu/200 \text{ MHz})^{-2.7}$ K
- Highly ‘confused’: 3 sources/arcmin^2 with $S_{0.2} > 0.1$ mJy

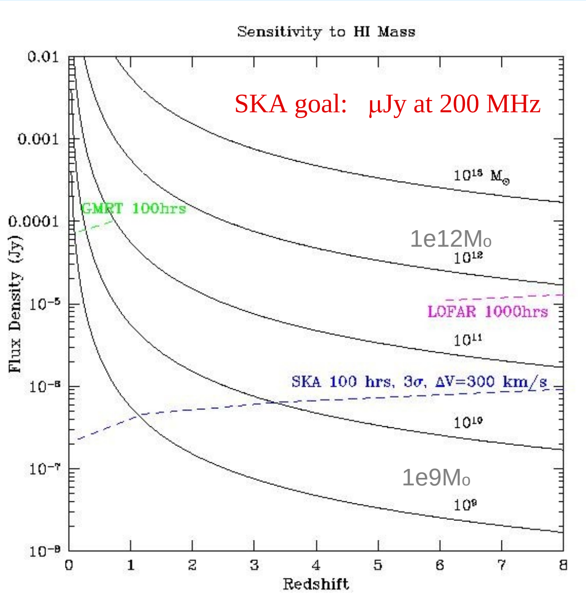

Eberg 408 MHz Image
(Haslam, 1982)

Solution: fitting in the spectral domain

courtesy C. Carilli

Studying the pristine IGM into the EOR, and beyond:

redshifted HI 21cm observations in range 30 – 200 MHz



Large scale structure: density, f(HI), T_{spin}

Very low frequency (<30MHz): pre-reionization HI signal

→ Lunar imperative: e.g., Baryon Oscillations (Barkana & Loeb)

<u>Very difficult to detect</u>

- Signal: 10 arcmin, 10mK

=> S_{30MHz} = 0.02 mJy

- SKA sens in 1000 hrs:

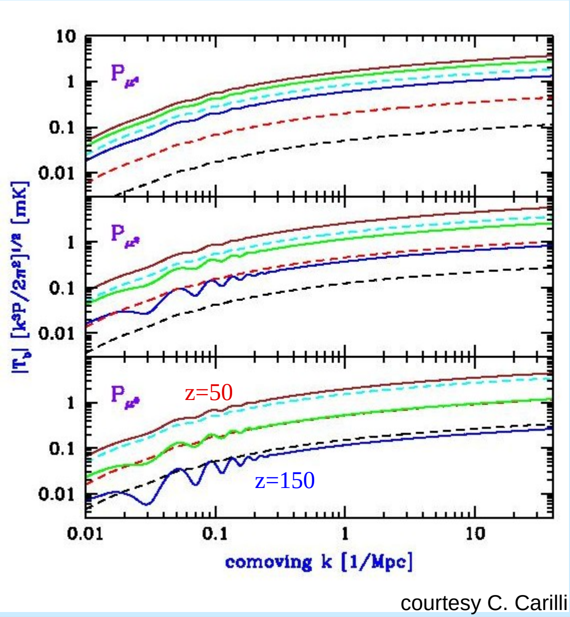
T= $100(\nu/200\ \mathrm{MHz})^{-2.7}$ K

= 20,000K at 30MHz =>

rms = 0.2 mJy

Need > 10 SKAs

Need DNR > 10^6

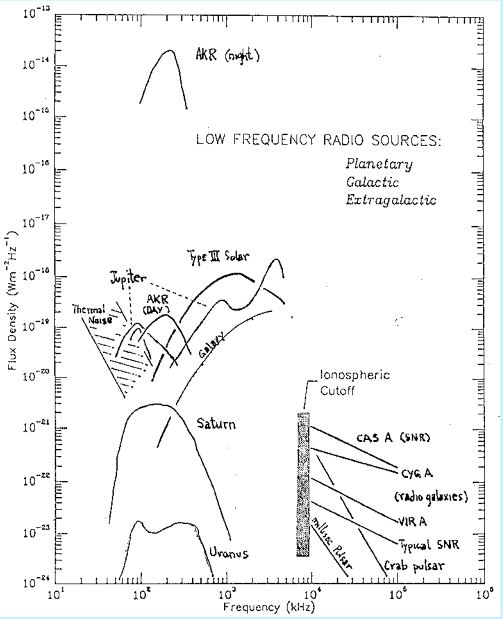


courtesy C. Carilli

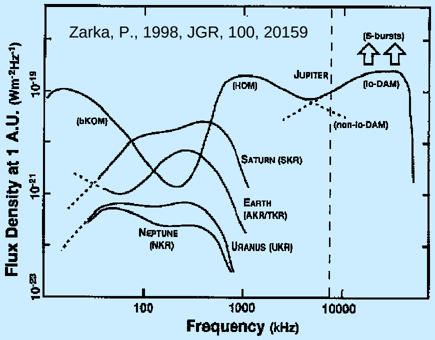
Advantages to Radio Observations from the Moon

- No interference from radio/TV broadcasting.
- No atmospheric distortions.
- Ability to observe the universe at ultra low-frequencies (<15 MHz, redshifts =100-1000) which are blocked by the ionosphere.

Low Frequency Environment from the Moon

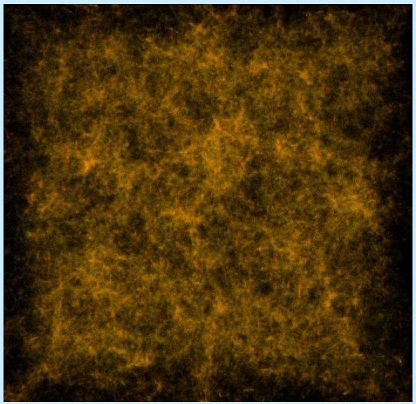


- >1 MHz interference is from Earth ionospheric breakthrough.
- <1 MHz interference comes from Earth's auroral kilometric radiation (AKR) peaking at 200 kHz.
- Cyclotron radiation from magnetospheres of all the planets at 100's of KHz.
- Type III solar bursts.
- Milky Way becomes opaque at <2 MHz.


Zarka, P., 1998, JGR, 100, 20159

Exciting Science at Long Radio Wavelengths

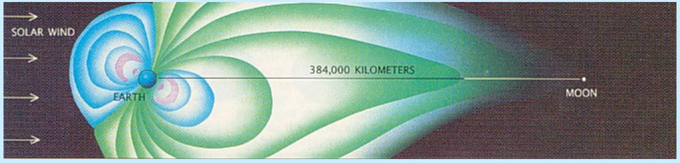
Baryons in z=10 universe from simulations



• ***Epoch of Reionization*** – When was "first light" in the Universe? Epoch of formation of the first sources of ionizing radiation from redshifted HI in emission and absorption (z = 6-50).

• ***Extrasolar Planets –*** Can modulated electron cyclotron emission from extra-solar planets be detected at low frequencies?

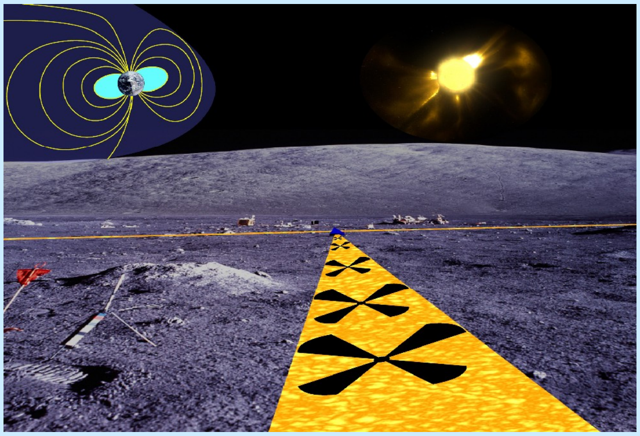
• ***Particle Acceleration –*** What are the low energy "seeds" from which the highest energy particles result?



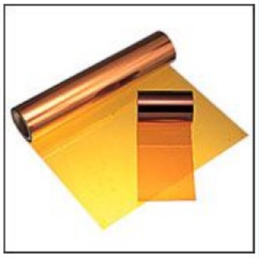
ROLSS: Radio Observatory for Lunar Science Sortie

J. Lazio & K. Weiler, NRL; R. MacDowell, L. Demaio, N. Gopalswamy, & N. Kaiser, GSFC;
J. Burns, U. Colorado; D. Jones, JPL; S. Bale, U.C.-Berkeley; J. Kasper, MIT

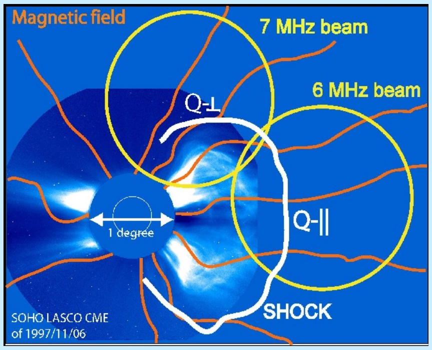
- A Pathfinder for a future long-wavelength farside lunar array (10-100 sq. km) targeting EoR, extrasolar planets, etc. -- interferometers grow as you go.
- Operating at 1-10 MHz (30-300 m), produces factor of 10 increase in resolution (<1º at 10 MHz) and sensitivity over previous space missions (e.g., RAE).
- Array consists of three 500-m long arms forming a Y; each arm has 16 antennas.



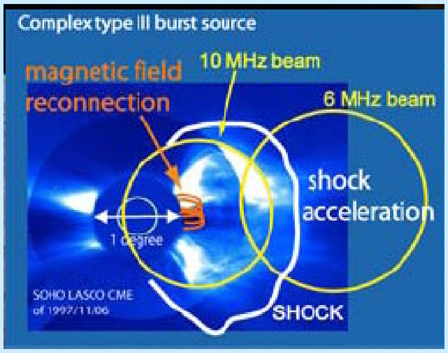
- Arms are a thin polyimide film on which antennas & transmission lines are deposited.
- Arms are stored as 25-cm diameter x 1-m wide rolls (0.025 thickness).



Solar Science with ROLSS



Type II Burst source location



Complex Type III source location

- ROLSS will produce the first high angular resolution (<1º at 10 MHz), high time resolution images of solar radio emissions (outer corona).
- ROLSS will determine source locations of coronal shock acceleration (Type II radio bursts) and magnetic field reconnection (Type III radio bursts).

VLA radio (green) image superimposed on optical image of the nearby radio galaxy Centaurus-A (Clarke & Burns).

More Science with ROLSS: Shock Acceleration in Radio Galaxies

- For nearby, luminous radio galaxies such as Cen A, ROLSS will detect or set limits on the minimum electron energy (E<50 MeV).
- Diffusive shock acceleration believed to fail for $\gamma<2000$, corresponding to $\upsilon=10$ MHz for $B=1\ \mu$G.

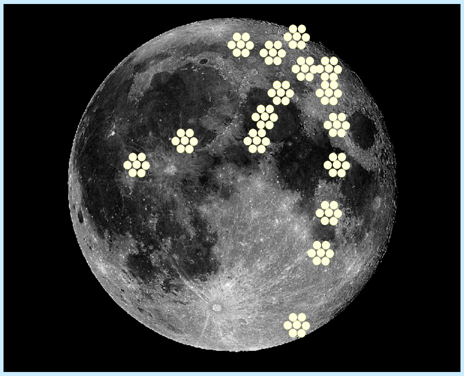
The Lunar Ionosphere

- Uncertainty about the density, geometry, & generation of a lunar ionosphere.
- A lunar atmosphere would have environmental implications for crewed operations on the Moon.
- Radio waves don't penetrate below the plasma frequency (9 kHz vn_e). Range of densities (100 to 5 x 10^4 cm^{-3}) imply frequencies 90 kHz - 2 MHz.

ROLSS will use background Type III solar bursts to set limits on lunar ionospheric cutoff.

Challenges for a Lunar Farside Array

Lunar Reconnaissance Orbiter (LRC)



- An environmental impact assessment of Moon is needed before serious planning for lunar telescopes can be conducted.
- What are the properties of the lunar ionosphere? (Measure from orbit or with ROLSS).
- How bad is RFI on the Moon now and for the future?
- Diffraction limits – how far do we need to be on the lunar farside? (How sharp is the knife’s edge?)
- Is a low power supercomputer needed for this array? (LOFAR is using an IBM Blue Gene with 0.15 MW).
- How cheaply can we build large collecting areas on the Moon?
- Can the radio instrumentation tolerate the lunar environment?