EPSC Abstracts
Vol. 8, EPSC2013-152, 2013
European Planetary Science Congress 2013

Low-frequency cosmology from the moon

M. Klein Wolt (1), A. Aminaei(1), H. Pourshaghaghi(1), L. Koopmans(2), H. Falcke(1)

(1)Department of Astrophysics Radboud University Nijmegen, Heijendaalseweg 135, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands, (M.KleinWolt@astro.ru.nl), (2) Kapteyn Astronomical Institute P.O.Box 800, 9700AV, Groningen, The Netherlands

Abstract

From a low-frequency point of view, the moon provides excess to the virtually unexplored radio frequency domain below 30 MHz that is not accessible from Earth due to the atmospheric cutoff and interference from man-made RFI. We show that with a single low-frequency radio antenna the detection of the 21-cm Dark Ages signal is possible within integration times of months, and address the size and integration times required for a future low-frequency array to perform detailed tomography and power spectral analysis of the Dark Ages signal.

1. Introduction

1.1. Low frequency astronomy and the moon

At frequencies below $\sim$ 100 MHz the turbulent variations in the Earth's ionosphere cause "radio seeing", and below $10-30$ MHz the ionospheric cut-off make it extremely difficult to perform high-resolution imaging of the radio sky. In addition the short-wave transmissions or Radio Frequency Interference (RFI) dominate the low-frequency radio spectrum and require special mitigation techniques. As a result, the best-quality images of the radio sky at low frequencies only reach a spatial resolution in the order of several degrees, which compares unfavorably with the sub-arc second resolution that can be achieved with current very-long baseline (VLBI) techniques at higher frequencies. In order to improve this situation space-based or moon-based low-frequency missions have been suggested already since the early 1970s. Currently, the only space missions that have been operated at these low frequencies are RAE-1 and 2 [4], but these had a poor sky coverage and limited angular resolutions (degrees). While space-based missions do not suffer from atmospheric effects, a large distance from Earth is required to reduce the RFI effects to a minimum (which puts heavy constraints on the communication and power requirements) and extreme and fast temperature variations in free space are not ideal. The moon on the other hand, provides the ideal location for low-frequency astronomy; with no atmospheric and ionospheric interference, locations that can provide significant (or complete) RFI attenuation (craters, mountains, polar locations or far-side locations) and stable temperature and gain conditions the moon is the preferred location to open up the virtually unexplored low-frequency domain.

1.2. Lunar Lander heritage

The European Lunar Lander (ELL) was planned to perform a soft-precision landing on the Lunar South Pole [1], hence providing an ideal opportunity for low-frequency astronomy. For this mission an active tripole antenna concept was designed, the Low Frequency eXplorer (LRX), operating in the kHz to 100 MHz regime. The LRX addresses a number of science cases, but the most dominant and challenging one being the detection of the 21-cm line from the Dark Ages (see [3] and [7] for a detailed description). The LRX was intended as a pathfinder concept and hence can be regarded a stepping-stone for any future large low-frequency radio array.

2. Cosmological Dark Ages

The Cosmic Microwave Background radiation was emitted at z$\sim$ 1200, about 400,000 years after the Big Bang, when the Universe had cooled off sufficiently for electrons and protons to recombine into neutral hydrogen atoms. However, although there were plenty of photons (these were scattered randomly) there were no sources of light in the Universe yet and hence this era is referred to as the Dark Ages, which continued to the Epoch of Reionization (EoR) when the first started to reionize the universe again (corresponding to redshift z=$11-1100$, see [6]). Throughout all the Dark Ages and the EoR hydrogen played a major role, emitting or absorbing the well-known 21 cm (1.4 GHz) line due to the spin flip of the electron. Today, this emission is redshifted by a factor $10-1000$ and lies in the $1.4-140$ MHz frequency range. Placing a single antenna on for instance the Lunar South Pole or Lunar far side, would allow for a detection of the 21-cm line but requires integration times in the order of months, stable conditions and accurate band-pass calibration [3, 2]. In addition, as the signal is expected to be a factor 10^6 weaker than the galactic background noise, significant attenuation of the RFI signal is required

3. Future opportunities

Although the LRX is expected to be able to detect the 21-cm signal, to answer questions like when did the EoR occur and which sources were responsible for the onset of the reionization, a much larger collecting area is required. A larger array providing arcminutes resolution and a sensitivity to measure mK brightness fluctuations would allow a detailed study of the tomography of the Dark Ages: by observing a different frequencies (and hence redshifts) one can trace the evolution of the first structures (Hydrogen and the Dark Matter coupled to it) in the early universe up to the EoR. In addition, power spectral analysis of the Dark Ages signal can provide density fluctuations on spatial scales less than 1', which will help to constrain cosmological models and predictions from current missions like WMAP and Planck.

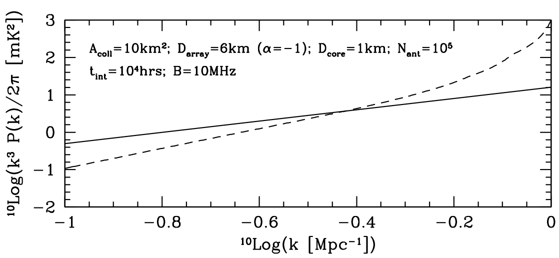

Figure 1: Sensitivity of a future LF interferometer. The solid line represents the brightness temperature variations according to [6] (i.e. the Dark Matter power spectrum), and the dashed line represents the sensitivity of an array with a collecting area of 10 km^2.

In order to achieve the high spatial resolution and sensitivity it is estimated that an array in the order of 10^5 individual antennas and integration times in the order of years are required [2]. For lower resolution (e.g. 10') this number can be reduced significantly ($\sim$ 3000 antennas). In Figure 1 we show that for an array with a collection area of 10 km^2 we are limited to below $^{10}log(k) = -0.4$ (wavenumber k=0.39) and at the lowest values the variations are too weak (below $^{10}log(k) = -0.9$; k=0.12) which corresponds to variations in the Dark Matter distribution of arcminutes; this can be improved by scaling the array or by larger integration time. Finally, one other major issue for all EoR experiments is the removal of the foreground removal. This requires a dynamic range of 10^6 and exquisite calibration at frequencies where the ionosphere is the worst. Hence, Space or moon is the best, albeit also most expensive, site for high-precision cosmology.

4. Summary and Conclusions

A low-frequency radio antenna on a RFI-quiet lunar location (i.e. South Pole, far-side) can address a wealth of science cases among which the detection of the 21-cm line from the Cosmological Dark ages is by far the most rewarding. With a single low-frequency antenna (on a RFI-quiet location) the detection of the 21-cm is possible within integration times of months. For a future low-frequency array to perform detailed tomography and power spectral analysis of the Dark Ages signal, collecting area's in the order of 10 km^2 and $\sim 10^5$ individual dipoles are required. The construction of such a large array, on the moon or in space, requires significant technology developments but provides an unprecedented view of the evolution of the early universe and is a treasure-trove for cosmology.

References

[1] Gardini, B., 2011, Memorie della Societa Astronomica Italiana 82, 422

[2] Jester, S., Falcke, H., May 2009, New Astronomy Review 53, 1–26.

[3] Klein-Wolt M. et al., 2012 P&SS, 74, 167

[4] Novaco, J. C., Brown, L. W., Apr. 1978, Astrophysical Journal 221, 114–123

[5] Pritchard & Loeb, 2008 Physical Review D, 78, 10, 103511

[6] Vol. 470 of American Institute of Physics Conference Series. pp. 13–+

[7] Zarka, P. et al., 2012, P&SS, 74, 156