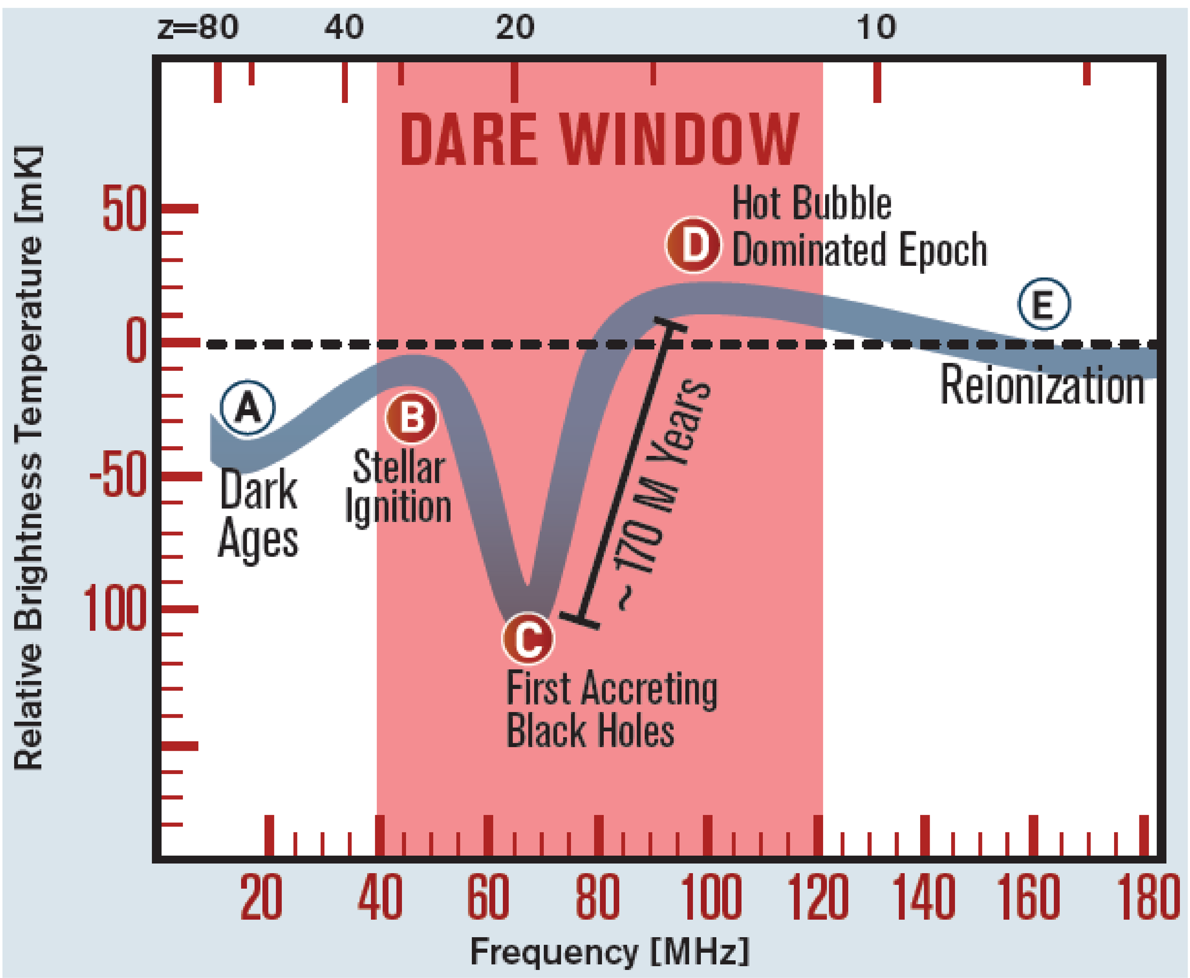
MCMC foreground subtraction for global 21-cm experiments

Geraint Harker

Center for Astrophysics and Space Astronomy, University of Colorado Boulder and NLSI Lunar University Network for Astrophysics Research

Introduction

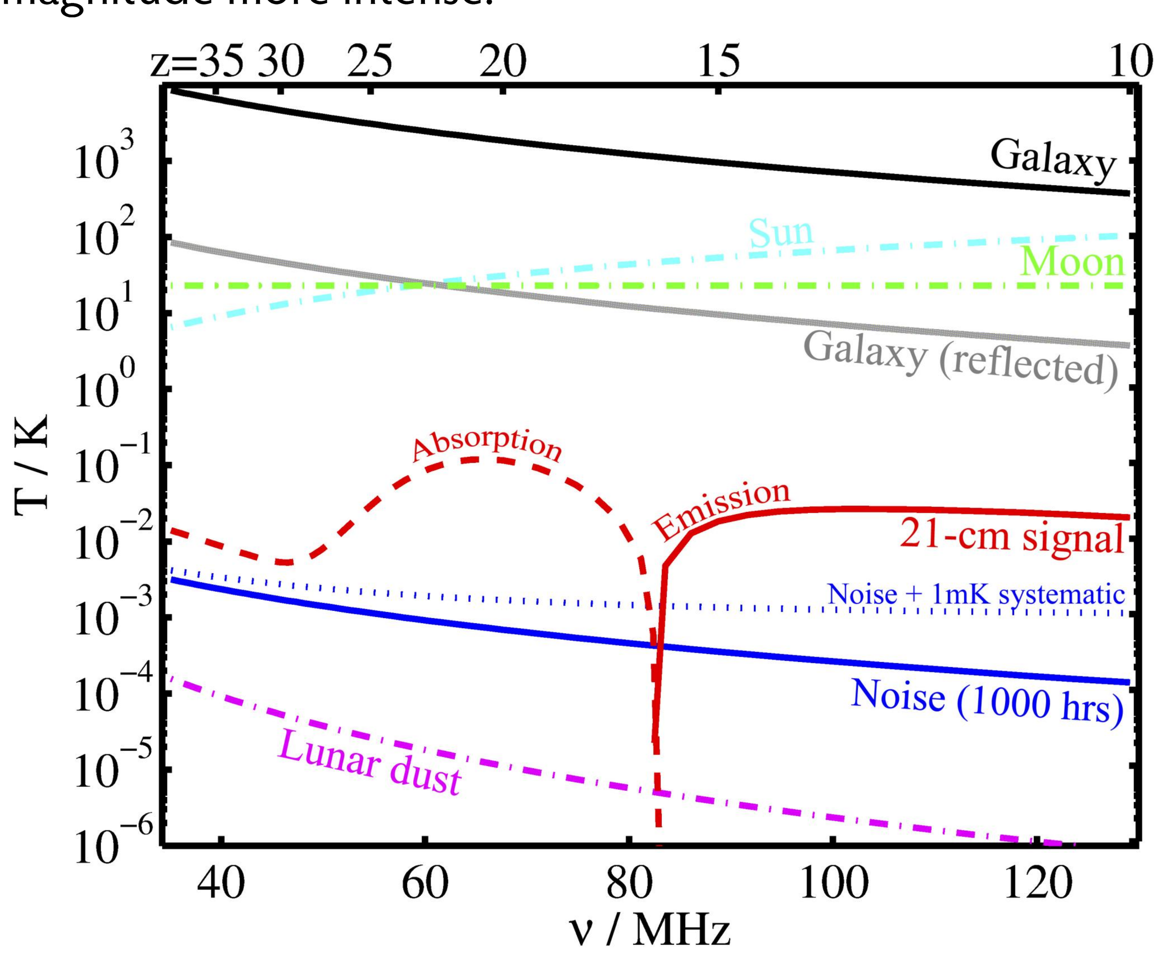
Sky-averaged observations of the highly redshifted 21-cm line will yield information on the first stars and galaxies, and the first accreting black holes



Models of the 21-cm spectrum[1] have *turning points* (A,B,C,D,E) whose positions encode the properties of the first sources of light in the Universe. The Dark Ages Radio Explorer (DARE) is an experiment to measure the position of turning points B,C and D from lunar orbit. A prototype for DARE is currently being deployed in Western Australia[2], near the similar EDGES experiment.

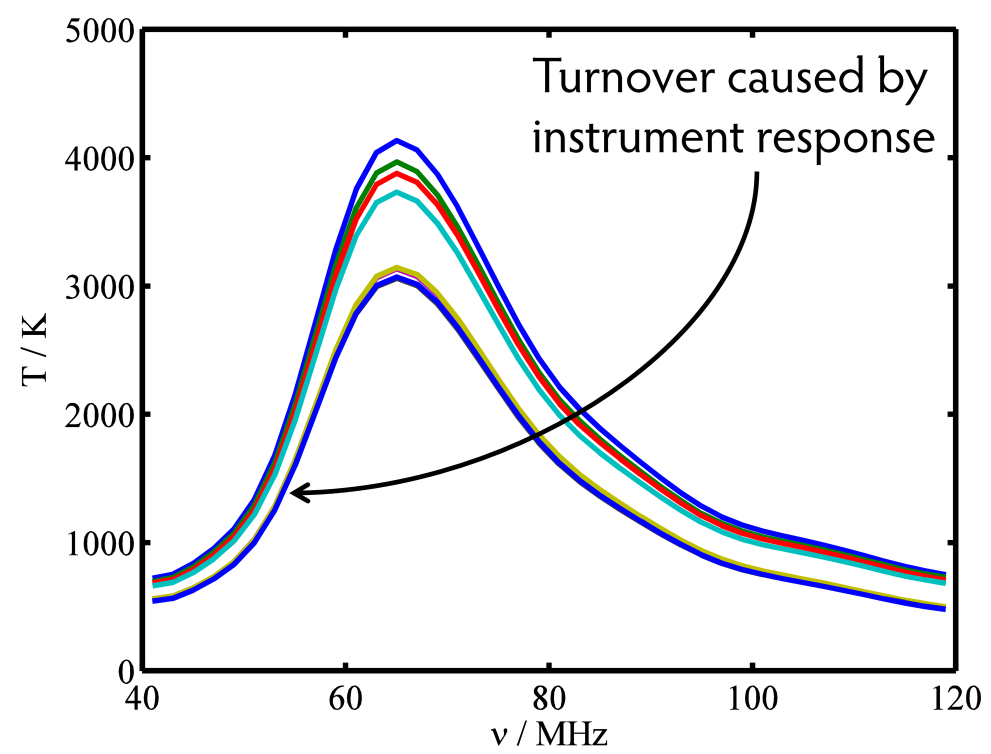
Foregrounds

At the low radio frequencies where the cosmological signal lies, there are many foreground sources which are orders of magnitude more intense.



Modeling data for DARE

Construct parametrized models for the signal, foregrounds and instrument. Generate synthetic data, then recover the parameters and their errors.



Noisy synthetic spectra from 8 DARE pointings (total 3000 h, or ~3 yr mission). DARE's large beam allows us to measure ~8 independent spectra (different foregrounds but same signal) from different directions.

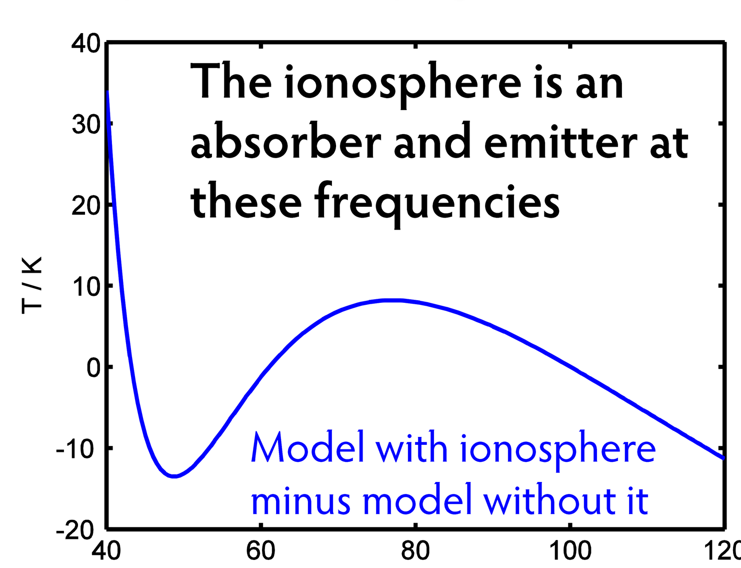
We developed a Markov Chain Monte Carlo code to estimate parameters and their errors. Correlations and degeneracies between instrument, foregrounds and signal are incorporated fully and consistently into the final results, and we can deal with a high-dimensional parameter space. Single step (no separate deconvolution/subtraction) improves dynamic range.

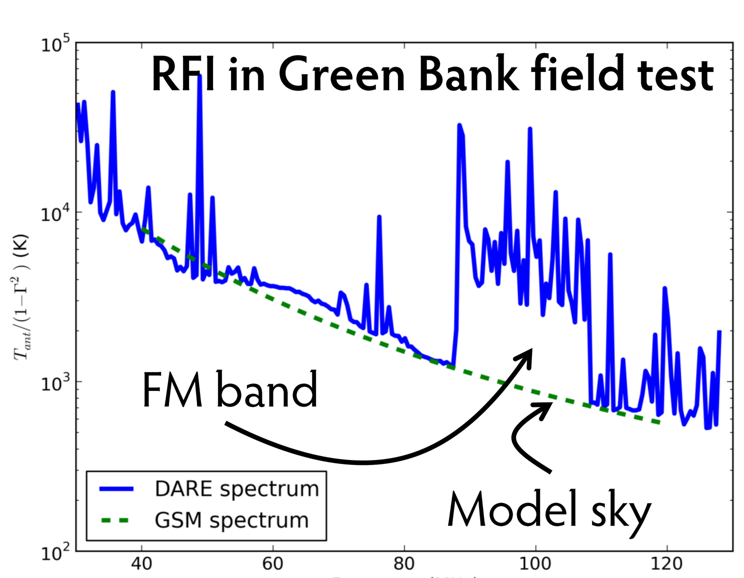
Parameter group	No. of parameters
21-cm signal (ν and T for each turning point)	2x3=6
Diffuse foregrounds (four parameters per sky area)	4x8=32
Sun (three for spectral shape, and eight normalizations)	3+8=11
Moon (temperature and reflectivity)	2
Instrument (frequency response, receiver temp.)	22
Total	**73**

An example of the number of parameters required to model a DARE data set, observing in eight different sky areas from lunar orbit. Including the ionosphere (for ground-based experiments) adds two parameters per sky region, but fewer independent sky areas are accessible from the ground, and lunar parameters are not needed.

Complications from the ground

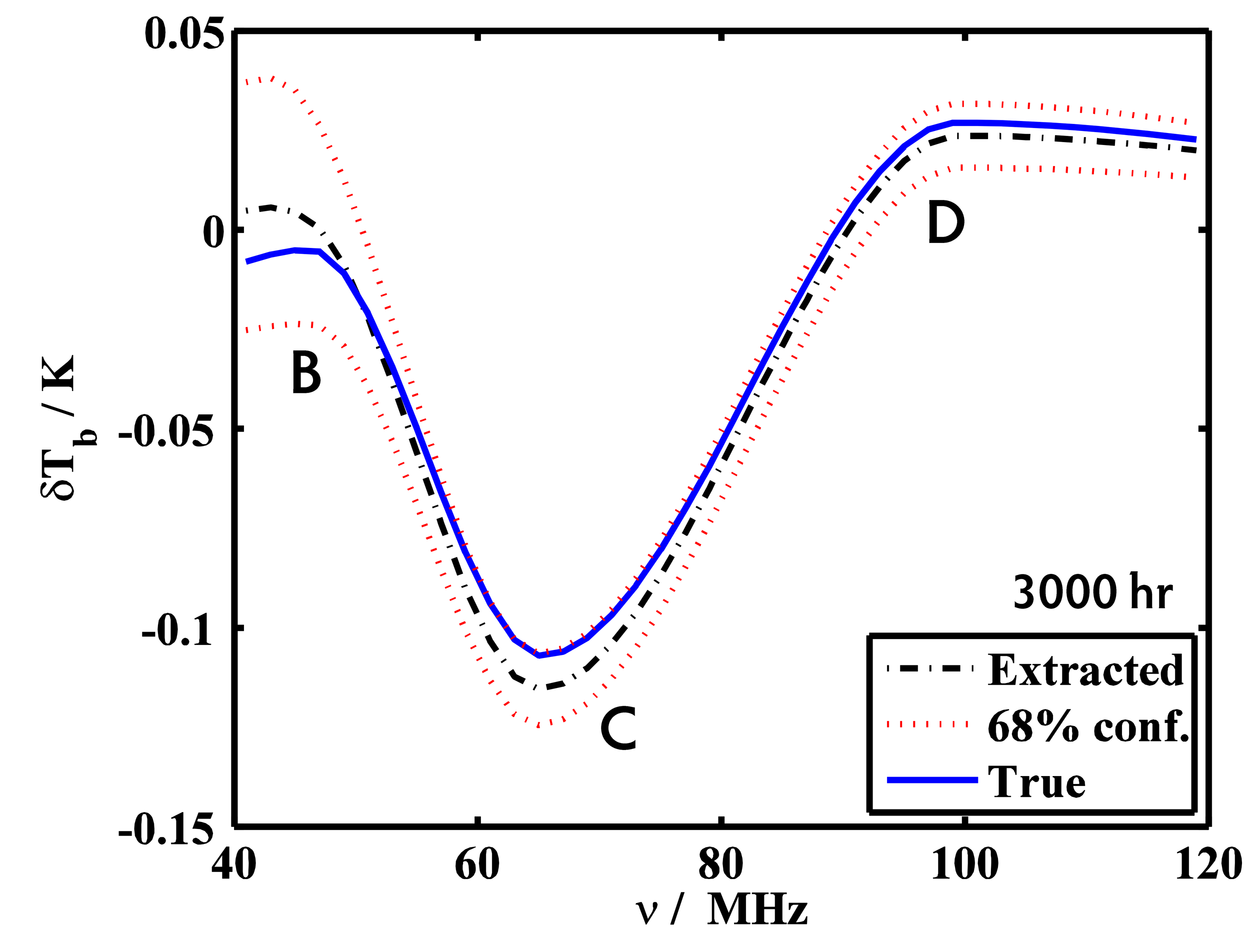
Must deal with a variable environment (temperature, humidity…), the ionosphere, anthropogenic radio frequency interference, reflections…



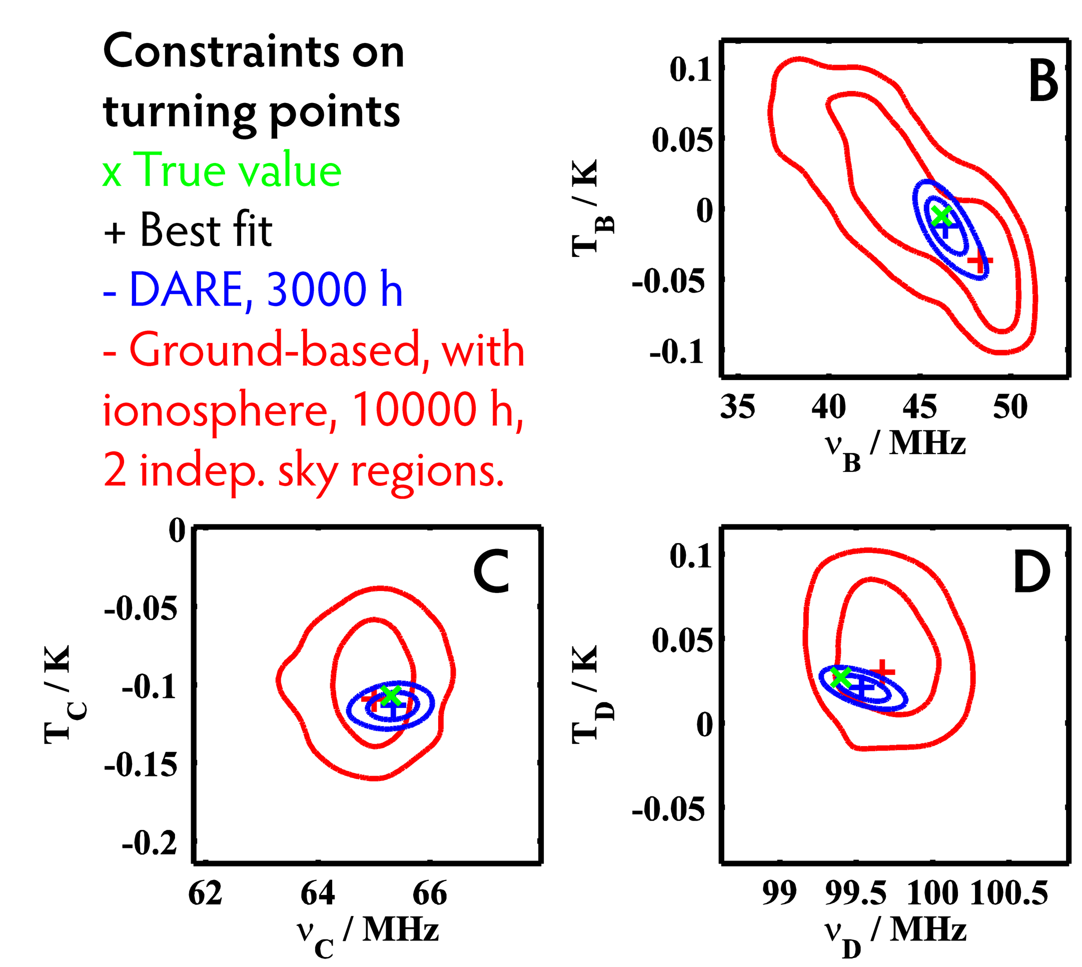


Results

MCMC chains converge within a few hours on a standard desktop machine. We recover the position of all 3 turning points with 3000 h of data (~3 year mission). 1000 h enough to get turning points C and D. More time and better sensitivity mainly improves turning point B.



Inferred constraints on the 21-cm spectrum for the fiducial DARE mission. Uncertainties computed after marginalizing over all foreground and instrumental parameters. The frequencies of the turning points are very well constrained, and the errors on the temperatures are correlated: most of the uncertainty is in the overall normalization of the spectrum, not the shape.



Inferred parameters and 68% and 95% confidence regions for the positions of the three turning points. We compare the fiducial DARE mission constraints with a ground-based experiment that integrates for 10000 h. For the latter we must fit extra parameters for the ionosphere: the resulting degeneracies place a fundamental limit on the accuracy that can be achieved from the ground. RFI and environmental variations are ignored, and a highly idealized ionospheric model is assumed. For DARE, the most important factor in achieving good constraints is the precision with which the instrumental parameters are known.

Conclusions

The DARE satellite can constrain turning points B, C and D within 3000 h, or turning points C and D within 1000 h. Field tests of a prototype are under way but it is already clear that taking data over the lunar farside has great advantages over a ground-based experiment. **Future work:** make use of a third party code to implement *nested sampling*[3] instead of MCMC: deal with complicated likelihoods and be able to compare Bayesian evidence for different models. For this, make use of Janus supercomputing facility at U. Colorado. Implement alternative signal histories, and model changes due to temperature, rain, etc. Use full circuit-theory models of the receiver system (being developed by Rich Bradley at NRAO) to improve realism of instrument modeling. Examine how having full time-resolved data rather than a limited number of integrated spectra can affect parameter inference.

Further information

An MCMC approach to extracting the global 21-cm signal during the cosmic dawn from sky-averaged radio observations; Harker G.J.A., Pritchard J.R., Burns J.O., Bowman J.D.; *Mon. Not. R. Astron. Soc.*, **419**, 1070

Probing the first stars and black holes in the early Universe with the Dark Ages Radio Explorer (DARE); Burns J.O., Lazio T.J.W., Bale S., Bowman J.D., Bradley R., Carilli C., Furlanetto S., Harker G.J.A., Loeb A., Pritchard J.R.; *Adv. Space Res.*, **49**, 433

Email me: geraint.harker@colorado.edu

References

[1]Constraining the unexplored period between the dark ages and reionization with observations of the global 21 cm signal; Pritchard J.R., Loeb A.; *Phys. Rev. D.*, **82**, id. 023006

[2]See poster 131.02 by Abhirup Datta in this session.

[3]MULTINEST: an efficient and robust Bayesian inference tool for cosmology and particle physics; Feroz F., Hobson M.P., Bridges M.; *Mon. Not. R. Astron. Soc.*, **398**, 1601

Acknowledgements

GH is a member of the LUNAR consortium, which is funded by the NASA Lunar Science Institute (via Cooperative Agreement NNA09DB30A) to investigate concepts for astrophysical observatories on the Moon.

LUNAR UNIVERSITY NETWORK for ASTROPHYSICS RESEARCH

University of Colorado Boulder