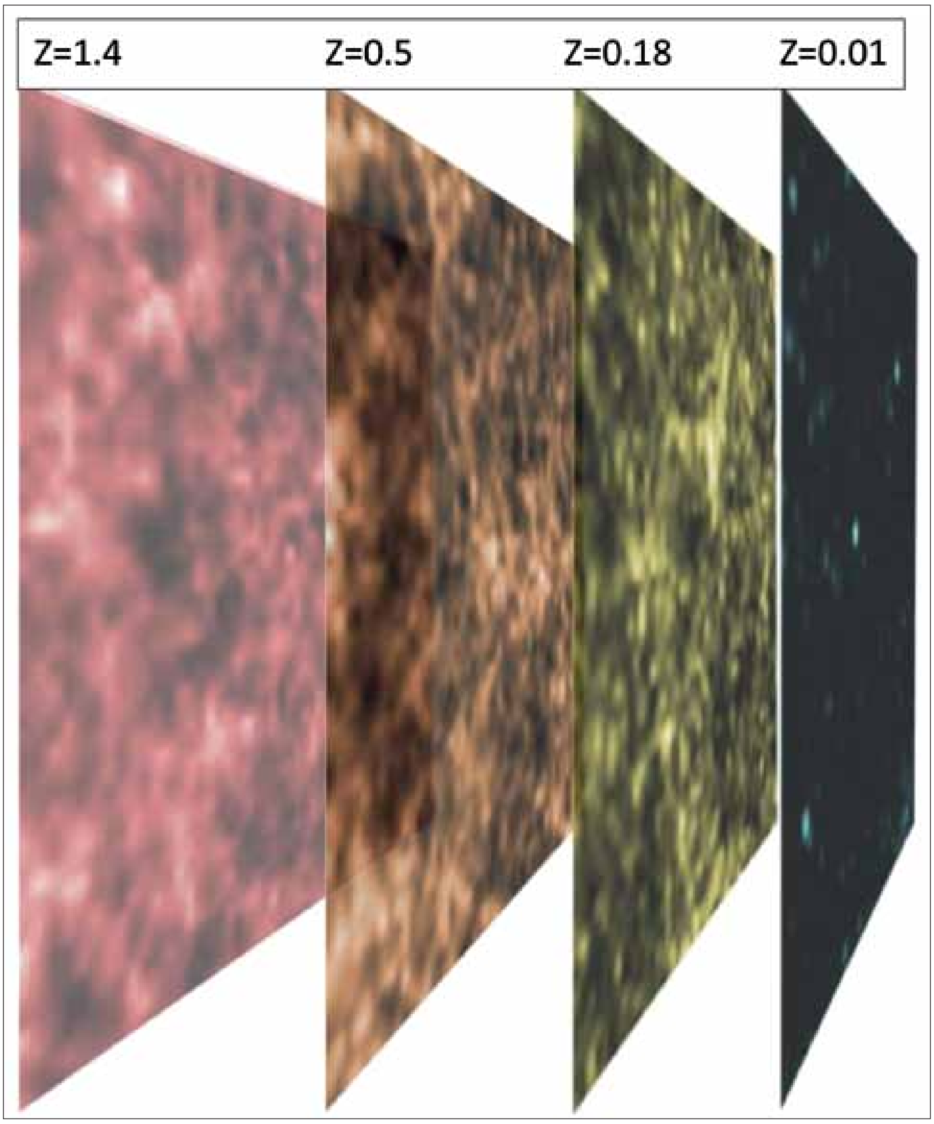
Radio intensity mapping: a new cosmological tool

Meeting report Ian Browne reports on a meeting discussing alternatives to major spectroscopic surveys for parameters such as the baryon acoustic oscillations – an artisan approach to obtaining cosmological data.

Cosmologists are always looking for standard candles or standard rulers in order to test and refine their models of the universe. Baryon acoustic oscillations (BAOs) have a characteristic linear scale which is well predicted from basic physics (~150 Mpc), making measurements of the BAO angular scale as a function of redshift a powerful cosmological test. These same BAO are responsible for the acoustic peaks and troughs now familiar in cosmic microwave background (CMB) power spectra. Measuring the scale of the BAO at much lower redshifts probes epochs at which dark energy starts to dominate the dynamics of the universe and thus the study of BAO is particularly suited to constraining the equation of state of dark energy. Effort in this area to date has been concentrated on huge optical spectroscopic surveys in which redshifts for millions of individual galaxies are measured. The distribution of light from galaxies is used as a proxy for the distribution of total mass. Controlling systematics is a challenge but impressive measurements of the acoustic scale have been obtained, most notably in BOSS (Anderson *et al.* 2014) and WiggleZ (Blake *et al.* 2012).

There is huge potential for using radio measurements of the redshifted 21 cm hydrogen line emission (again as a proxy for the total matter distribution) from individual galaxies to study BAO. Indeed, this has been one of the science drivers behind the Square Kilometre Array (SKA). It will, however, be a long wait before SKA can deliver results on sufficient numbers of individual galaxies: the full SKA1 is scheduled to start work in 2023 and should detect about a billion galaxies. In the meantime, the alternative technique of intensity mapping offers the prospects of relatively quick results for relatively little money and with completely different systematics from those in optical surveys.

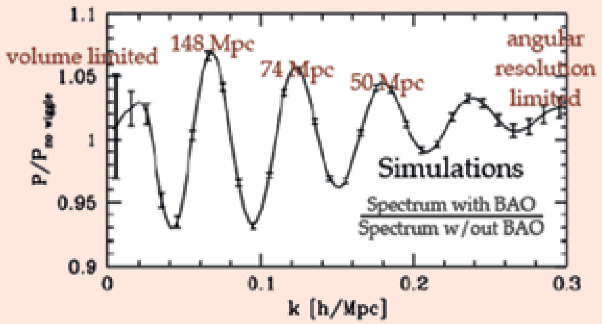


1: Redshift slices of the universe seen in neutral hydrogen emission. At the lower redshifts (right) the emission is dominated by that from individual galaxies and groups while at the higher redshifts (left) the emission is concentrated within clusters and super-clusters. Each panel represents a four square degree patch of sky and the emission is averaged over 50 MHz. (Kate Voller)

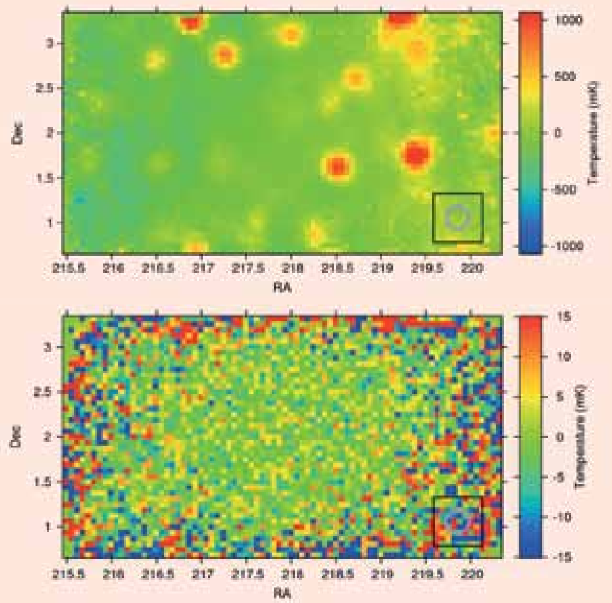
New and existing instruments

The RAS Specialist Discussion Meeting "Radio intensity mapping as a new cosmological tool" held on 9 May focused on progress being made both with existing radio telescopes and particularly on new radio instruments specifically designed for intensity mapping. This report is based on talks given at that meeting, most of which are available at http://www.jb.man.ac.uk/research/BINGO.

The magic of intensity mapping using the 21 cm line of neutral hydrogen is that there is no need to measure each individual galaxy; one allows the naturally broad beam of a radio telescope to integrate up the hydrogen emission from perhaps thousands of galaxies simultaneously and thus obtain the three-dimensional distribution of gas. Such an approach works only because hydrogen emits a single emission line; once detected, the redshift comes for free. For BAO studies it is also fortunate that the angular scale of the BAO is well matched to that of typical radio-telescope beams, i.e.



2: A simulated power spectrum with error bars calculated using the expected performance of the CHIME instrument. To make the BAO wiggles visible, a smooth fit to the power spectrum has been subtracted. For small values of *k*, i.e. large physical scales, the errors are dominated by cosmic variance. The angular resolution of the instrument is chosen to sample the main angular scales of interest. (Jeff Peterson)



4 (Top): GBT data before foreground subtraction. (Bottom): Map after foreground subtraction. Note the temperature scales are very different and that the point sources have been successfully removed. (Ue-Li Pen)

3: The Green Bank Telescope is part of the National Radio Astronomy Observatory site in West Virginia, USA.

around half a degree at wavelengths less than 21 cm where redshifted hydrogen emission can be measured. Figure 1 illustrates how the universe might appear if we saw only the neutral hydrogen emission. The number of galaxies in a beam increases with increasing redshift, thus on the rightmost panel the hydrogen appears concentrated in a few individual galaxies whereas at the higher redshifts, shown on the left, it appears much more diffuse. This is because we then see the integrated emission from thousands of galaxies. Detecting redshifted hydrogen may look easy but the reality is that the integrated emission from the hydrogen in galaxies is more than three orders of magnitude weaker than that from other sources of radio emission, mainly that from our galaxy. Very long integration times (many hours per pixel) are needed to reach the required sensitivity (~100 μK) and then the hydrogen emission needs to be disentangled from galactic foreground emission which, at these frequencies, is predominantly synchrotron and free–free emission. The saving grace is that the foreground emission has a very smooth, almost power-law, spectrum whereas the integrated emission from hydrogen, by definition, varies with frequency. Just being able to quantify how the neutral hydrogen emission varies with redshift will be a strong constraint on structure-formation models; measurement of BAO scale in many ways will be a bonus.

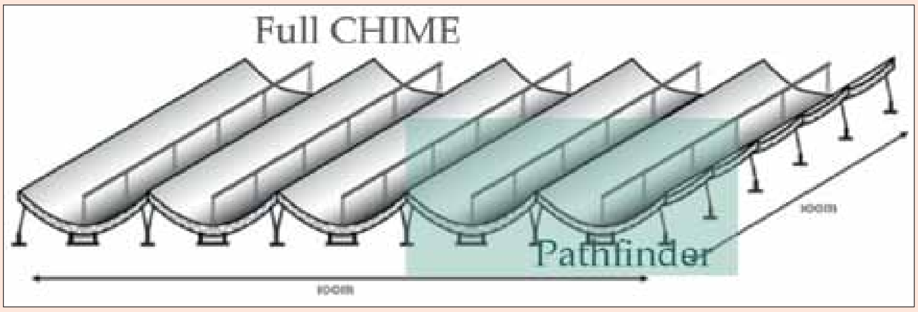
It is worth pointing out that there is a related area of research using the intensity mapping technique which aims to study the epoch of reionization (EoR) looking for hydrogen emission at redshift around 10. This interesting topic was not covered in the meeting but shares many of the same challenges.

The state of the radio art

The ideas for hydrogen intensity mapping were developed several years ago, most notably by Battye *et al.* (2004), Chang *et al.* (2008) and Peterson *et al.* (2006). Since then activities have focused on three main areas: simulating the expected signal, trying to detect the integrated hydrogen emission with existing instruments, and designing and building instruments with the specific aim of being able not only to detect the integrated hydrogen emission but also to characterize the BAOs. At the meeting **Ue-Li Pen** (Canadian Institute for Theoretical Astrophysics [CITA]) presented simulations of the expected signal and discussed in detail how one might extract the hydrogen signal from the foreground emission. He showed that foreground subtraction should work and the hydrogen signal recovered. An example of the type of detection of the BAO signal that might be expected for CHIME, one of the new instruments described below, is shown in figure 2. This is a simulation of the power spectrum of the hydrogen distribution. In order to make the BAO more visible, the smooth fit to the spectrum has been subtracted.

Similarly, predictions for other instruments such as BINGO (BAO from Integrated Neutral Gas Observations), were presented by **Marie-anne Bigot-Sazy** (Manchester) and **Clive Dickinson** (Manchester). Pen also discussed the results of the initial measurements he and his colleagues have made with the Green Bank Telescope (GBT; figure 3) in the frequency range 400 MHz to 800 MHz (redshifts 2.5 to 0.8). Using an existing radio facility for intensity mapping has the clear advantage that one can simply apply for observing time. The disadvantage is that to do anything useful requires lots of observing time – one is in competition with other users – and that the instrumental performance is unlikely to be as good as one specifically designed for the task. But simply by trying, one learns a lot about how to tune future instruments and data analysis techniques.

The GBT is the only instrument delivering results. The GBT map of a patch of sky 3.5° × 3.5° is shown in figure 4, both the raw map and what's left after the best attempt has been made to remove "contaminating signals". The raw map is of a single frequency channel. Other channels show the same extragalactic sources (spots) but have a different hydrogen signature, which is how the latter is separated from the contaminating signals. Two methods of analysis yield a positive result. Cross-correlation with the known positions and redshift of optically detected galaxies in the same area gives a clear statistical detection. At a lower level of significance there is a claim of a direct detection of a signal with the correct properties to be redshifted hydrogen emission.



5: The CHIME antenna configuration. The "pathfinder", shown shaded, comprises two 20 m long cylinders. The full instrument will consist of five 100 m cylinders. (Jeff Peterson)

6: The site for the BINGO telescope in an abandoned gold mine in Uruguay (Clive Dickinson). The 3D map (right) of the Castrillon Mine (kindly provided by the Orosur Mining company) shows the approximate location of the telescope. (Adrian Galtrass)

It took 190 hours of integration with the biggest and best radio telescope in the world to make this bare detection; obtaining enough signal to characterize the BAO scale is clearly a challenge.

What can be done better? **Jeff Peterson** (Carnegie Mellon University) described one obvious way, which is to replace the existing single-pixel feed on the GBT with an array of seven feeds at the focus. This is not trivial, but Peterson described an innovative design which should enable the seven feeds to be fitted in the limited space available and yet maintain good performance.

In this context good performance means a beam with very low sidelobes to minimize the pickup of contaminating signals in sidelobes. Excellent polarization discrimination is also important. This is a subtle but nevertheless important lesson learnt from the GBT experience. Galactic synchrotron emission is linearly polarized and its position angle changes with frequency because of Faraday rotation. If some of this linearly polarized signal "leaks" into the unpolarized total intensity map used to look for the hydrogen emission, because of the polarization position angle change with frequency, the polarization leakage will be frequency-dependent and thus mimic the hydrogen emission. Ue-Li Pen emphasized that this is an important design consideration for future telescopes.

As well as the GBT, other large radio telescopes around the world are stepping up to the BAO challenge. On the 64 m Parkes Telescope in Australia, the existing 13-beam receiver system is being upgraded to give better noise performance and improved signal-processing capability, while the Effelsberg 100 m telescope in Germany will have a phased array feed installed which will give many simultaneous beams to improve the survey speed.

New instruments in the pipeline

As befits a research area in its infancy there are many different approaches being tried. Should one use a single dish, a conventional interferometer array, or even something in between? Is it wise to build an instrument that focuses ruthlessly on BAO, or compromise by adapting a general-purpose instrument? All options are being pursued. The most advanced special-purpose instrument is CHIME (Canadian Hydrogen Intensity Mapping Experiment; figure 5) whose first phase is under construction in Penticton in Canada. The novel feature of CHIME is that ultimately it will use five 100 m long and 20 m wide fixed cylindrical antennas with their axes aligned north–south, forming an interferometer. The great advantage of the cylinder antennas is that by cross-correlating the signals for feeds along the line of focus of one cylinder with the all the feeds of the others, a wide range of declinations can be sampled simultaneously with almost circular beams. By exploiting the Earth's rotation, nearly half the sky can be mapped in 24 hours. Of course, hundreds of days of observations will be required to beat down the noise.

A pathfinder consisting of two 40 m by 20 m cylinders has been constructed and the first interferometer fringes have been detected. If all goes well the full CHIME instrument should yield a great measurement of BAOs (figure 2). If there is a concern about CHIME, it is how well behaved the synthesized beams are and how any uncontrolled sidelobes may affect the separation of the signal of interest from the other contaminating signals, both astronomical and those originating on Earth.

This comes back to the key issue of extracting the desired signal in the presence not only of astronomical foregrounds but also manmade interference (RFI) and calibration uncertainties, something that will face all instruments, and thus formed a major part of the RAS discussion programme. In particular, RFI issues were addressed by **Christian Monstein** (ETH, Zurich). There is nowhere in the world where it is possible to hide from RFI, so clever techniques have to be used to enable bad data to be excised.

The desire to have very clean beams (PSFs in optical parlance) has been the main motivation behind the design of another new instrument, BINGO, proposed by groups from the UK, Brazil, Switzerland, Uruguay and Saudi Arabia.

At the meeting, BINGO was described by **Richard Battye** (Manchester; Battye *et al.* 2013). Like CHIME, it's a telescope with no moving parts but its design is firmly based on experience with conventional CMB instruments. Correlation receivers will be used as in WMAP and Planck and the optics will follow a two-mirror compact range design used in ground-based CMB work. This optical design offers a wide field of view (more than 15° instantaneously) and excellent polarization purity. The plan is to construct the telescope in a disused gold mine in northern Uruguay (figure 6), using the shape of the mine to help support the structure as well as to provide some shielding from radio interference. A novel feature will be the use of the south celestial pole as sources of the reference signals for the 50+ correlation receivers at the focus. Every new instrument presents its own challenges and the major one for BINGO is how to fabricate economically the 50 or more huge horns for the array at the telescope focus. As an illustration of a new use for everyday materials, the meeting was shown a picture, figure 7, of a prototype feed-horn built up out of a stack of plates made from 25 mm insulating sheets of builder's foam, plus copper tape. It works!

7: Looking into a prototype feed horn for BINGO during construction. It is made from discs of builder's insulating foam, which have aluminium foil on both surfaces; copper tape makes the electrical contact between the top and bottom surfaces when the foam is cut. It all works! (Ian Browne)

BINGO adopts a pure single-dish approach and CHIME adopts a hybrid dish/interferometer approach. Pure interferometer instruments using arrays of relatively small dishes are also being explored. **Reza Ansari** (Paris) described the work being done in France in collaboration mainly with China on digital instrumentation and initial investigations of a close-packed interferometer made out of an array of small single dishes. Interferometers are fundamentally more stable than single dishes because they measure just that part of the receiver output which is correlated between the dishes and not the uncorrelated noise introduced by the receivers themselves. Chinese, French and US groups have a project called Tianlai to build a BAO instrument in Xinjiang province, either from an array of small dishes or from cylindrical antennas like CHIME. The chosen site is remote and exceptionally radio quiet.

Something different

Hydrogen is abundant and, when in neutral state, produces a single emission line, making it the ideal for intensity mapping. But highly redshifted CO emission offers another exciting opportunity, this time for tracing the evolution of molecular gas in the universe. **Jamie Leech** (Oxford) outlined the design of a pathfinder instrument consisting of two small telescopes, one working in the range 13 to 20 GHz and the other 26 to 40 GHz. The wide frequency coverage is required in order that more than one line of the CO rotational series can be seen simultaneously and thus the redshift fixed without ambiguity.

Phil Bull (University of Oslo) talked about the work he and his colleagues have been doing on quantifying the cosmological "power" of present and of future intensity-mapping experiments (Bull *et al.* 2014). Not surprisingly, the full SKA comes top of the league although the SKA pathfinder telescopes will be powerful instruments in themselves. But an innovative technique will be required to harness their power. Even SKA will have relatively sparse spatial frequency coverage when it comes to intensity mapping and thus the surface brightness sensitivity in conventional synthesis-mode will not be good enough to pick up the low-brightness hydrogen emission.

An autocorrelation technique will be required in which the spectra obtained by the individual telescopes are added together. Accurate calibration information should be available from using information from the cross-correlation of signals from the telescopes operating in conventional interferometric mode. Of course the resolution in this mode is limited by the size of the individual telescopes, which in the case of SKA and its pathfinders is 15 m, equivalent to a resolution of 2.5° for hydrogen at a redshift of unity. The power of SKA and its precursors for BAO studies will be strongest at lower redshifts where the linear resolution of the dishes is higher and the BAO angular scale larger. But this will not stop interesting results being obtained on the life history of hydrogen at much higher redshifts.

Last words

Cosmological science has made remarkable strides forward in the last 25 years, led mainly by theoretical insight about the early universe and exquisite observations of the CMB. Where theory does not lead is in the area of dark energy, believed to be responsible for the acceleration of the expansion of the universe. Observational clues are desperately needed. Huge, corporate astronomical projects such as the LSST (Large Synoptic Survey Telescope), Euclid and even SKA are stepping up to the mark and will begin to deliver results in around a decade. But there is still room for modest, artisan projects to make a significant contribution to the subject and this is where intensity mapping fits. This work is not without its challenges, but participants at the meeting were optimistic that they can be met within the next two or three years. Intensity-mapping projects provide an ideal training ground for the next generation of instrumentalists. Doing the observations will open up to scrutiny a new area of parameter space and might even turn up something completely new. We take inspiration from Tony Hewish and Jocelyn Bell Burnell and their discovery of pulsars. The next few years should be interesting. ●

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Acknowledgments. The author thanks the co-organizer of the meeting, Fil Abdalla, and all those who contributed to the meeting and for making their material available. Thanks also to Maria Marcha for her comments.

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