

The First Galaxies

BY STUART WYITHE

New technologies are enabling astronomers to peer through a haze of hydrogen to when the first galaxies were born less than 1 billion years after the Big Bang.

Astronomers are mostly concerned with trying to understand how the Universe came to look the way it does. We believe that the Universe has a finite age and, as a result, that there must have been a time when galaxies appeared for the first time.

However, we do not know how this first generation of galaxies formed. We do not know what they looked like or how big they were. Indeed, we do not even know when galaxies first played an important role in the evolution of our Universe.

When astronomers observe the distant Universe they do not see it as it exists today, but rather as it looked at some time in the past. This is because it takes light a finite amount of time to travel from the place where an event actually happens to the place from where we later observe it. Thus astronomers are able to construct a “fossil record” of the history of the Universe by looking out to ever-larger distances.

This article looks at why our fossil record of the first galaxies remains incomplete, and what astronomers are doing to rectify this situation in the future.

The First Galaxies

Astronomers believe that our Universe began with the “Big Bang” (Fig. 1), which left small ripples of density in otherwise smooth space. Just after the Big Bang the Universe contained very hot gas, with hydrogen separated into its constituent proton and electron to form an impene-

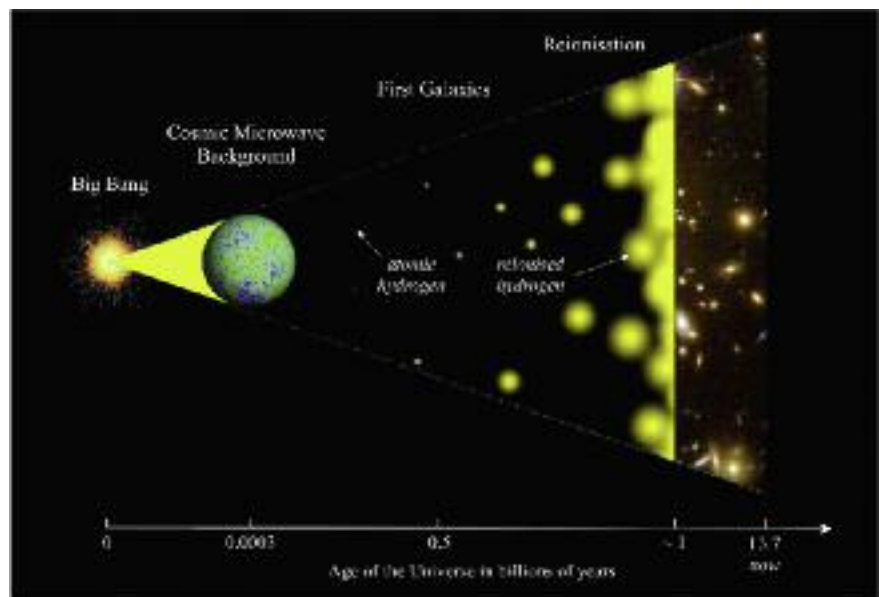


Figure 1. Schematic timeline of the history of the Universe. The age of the Universe is depicted along the horizontal axis, while the triangular shape represents the Universe's expansion with time. The most important events are labelled, including the Big Bang, the time of hydrogen recombination from which we observe the Cosmic Microwave Background at an age of 380,000 years, the formation of the first galaxies at around 500 million years, and the consequent reionisation of hydrogen at some time prior to an age of 1 billion years. In this figure, black represents regions of time and space in the Universe where hydrogen is in its atomic form, while yellow represents regions where it is split into its constituent proton and electron. Image: Paul Geil, The University of Melbourne

trable “fog” beyond which astronomers are unable to directly observe. Then, as the initially very hot Universe expanded and cooled, these small ripples of density grew with time under the influence of gravity, eventually forming the sites of modern-day galaxies.

When the Universe cooled sufficiently that the gas of protons and electrons “recombined” to form atomic hydrogen, light was able to travel freely for the first time. We observe this light today as a diffuse glow in the sky known as the Cosmic Microwave Background, which

describes the state of the Universe 380,000 years after the Big Bang.

The Universe wasn't a very interesting place back then. The Cosmic Microwave Background reveals a Universe in which the density was nearly constant everywhere, with only very tiny fluctuations. There were no planets, no stars, no galaxies – nothing.

One had to wait for the first galaxies to form, but for how long? We know that the Universe is populated with stars and galaxies today, 13.7 billion years after the Big Bang. Indeed, we see very massive

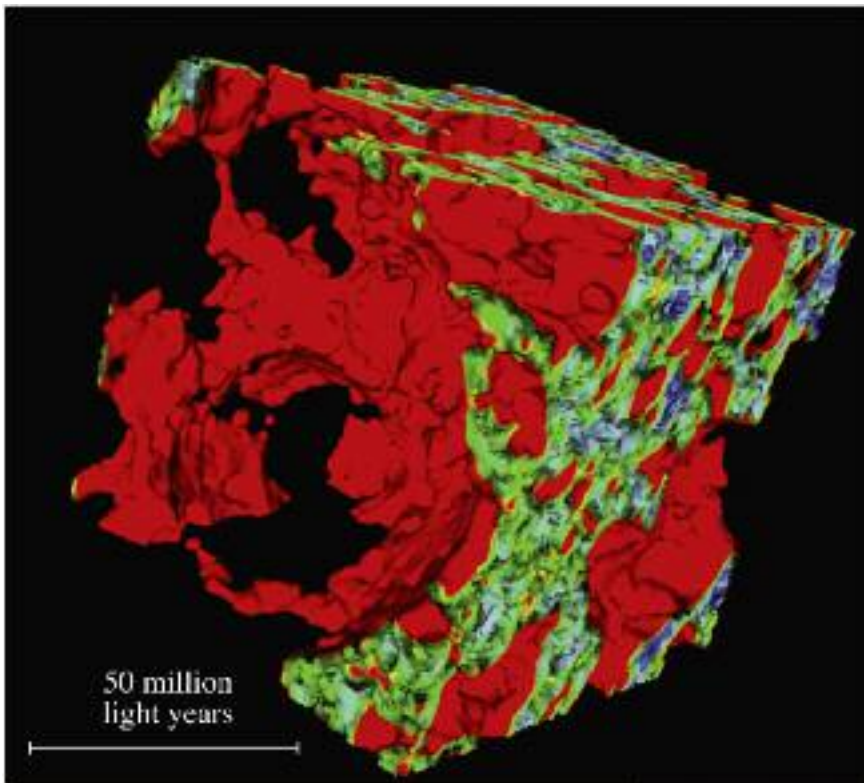


Figure 2. A computer simulation illustrating the three-dimensional structure of atomic hydrogen during the reionisation era. Theoretical models predict that the atomic hydrogen will not be reionised evenly throughout the Universe. Rather, the earliest galaxies will create ionised bubbles. In computer simulations, large collections of these bubbles give the distribution of atomic hydrogen the appearance of a sea-sponge, the three-dimensional structure of which could be measured using 21cm radiation. The large feature in the lower left of this figure corresponds to a region where many galaxies have clustered, producing a giant ionised bubble near the end of the reionisation era approximately 50,000 light years across. Many properties of the earliest galaxies, such as their mass and number, could be inferred by looking at these bubbles. Image: Paul Geil, The University of Melbourne

galaxies that existed as long as 12.7 billion years ago, a mere 1 billion years after the Big Bang.

However, these galaxies were comparable in size to the most massive galaxies in the nearby Universe. As a result they are not thought to have been the original galaxies because small galaxies are believed to have formed before large ones in a process called hierarchical structure formation.

Astronomers will therefore have to look back to earlier times to find the first, smaller galaxies. Unfortunately, these very distant galaxies are faint and thus difficult to discover. The hunt for the first galaxies is still a long way from over.

Reionisation of the Universe

If galaxies are going to be very hard to find during the first billion years of the

Universe's history, how will astronomers be able to study them? The answer is to look at how the galaxies affect the rest of the Universe, rather than look at the galaxies themselves.

Most of the "normal" matter in the Universe is hydrogen, and hydrogen is found in its atomic form 380,000 years after the Big Bang. Some of this atomic hydrogen will form stars within galaxies, but most is located in the space between galaxies.

When the first stars and galaxies form, the ultraviolet part of their light has sufficient energy to break or "reionise" this "intergalactic" atomic hydrogen back into its constituent proton and electron. One could therefore define the time when galaxies first became important as the instant when the combined galaxies in the Universe had produced enough ultra-

violet light to reionise all of the hydrogen. Astronomers refer to this time as the end of the reionisation era.

Thus, rather than try to find the earliest galaxies directly, astronomers could instead look at the state of the hydrogen between the galaxies. If the end of the reionisation era could be measured, then this would provide our first evidence for the epoch when the earliest galaxies formed.

But how would astronomers go about looking for atomic hydrogen between galaxies? Fortunately, under the right conditions, atomic hydrogen emits radio waves at a wavelength close to 21cm. Astronomers have used this 21 cm radiation for decades to study the structure and dynamics of our galaxy, the Milky Way, as well as to look for new galaxies.

The Universe is known to be expanding. Moreover, Hubble's law states that the greater the distance to a point in the Universe, the faster the expansion is observed to be. Hubble's law is normally discussed with respect to galaxies, but it also applies to the hydrogen between galaxies.

When studying the reionisation era, the point to understand is that while hydrogen atoms emit radiation at 21cm, the radiation will be seen to have a longer wavelength if the emitting hydrogen is at a large distance from the observer – a phenomenon referred to as "redshifting". As a result, the radio waves emitted by atomic hydrogen in different parts of space will be observed not at a wavelength of 21cm but at a wavelength that increases with distance. Astronomers will therefore be able to use Hubble's law to measure the distribution of atomic hydrogen in three dimensions (Fig. 2).

This measurement can only be made before the end of the reionisation era because a hydrogen atom that is reionised into its constituent proton and electron can no longer emit 21cm radiation. As a result, the hydrogen between the galaxies

becomes invisible once the reionisation era has ended.

Astronomers will be able to use the wavelength below which 21cm radiation is no longer observed to determine the time at which the atomic hydrogen was reionised by the first galaxies.

Reionisation and the Murchison Widefield Array

Why haven't astronomers already used 21 cm radiation to study atomic hydrogen during the first billion years of the Universe's evolution, and to determine when hydrogen was reionised by the first galaxies? The reason is mostly technology.

From observations of the most distant galaxies yet discovered we know that the frequency of the radiation carrying the signal from atomic hydrogen in the reionisation era will be smaller than 200 MHz, corresponding to wavelengths greater than 1.5 metres. These are very low frequencies compared with those of traditional radio astronomy, which throws up several significant obstacles – some man-made, and some intrinsic to the radiation itself.

However a consortium of radio astronomers from the US, India and Australia have accepted the challenge. To measure the end of the reionisation era this consortium is constructing a new purpose-built radio telescope in central Western Australia. Known as the Murchison Widefield Array (MWA), this project heralds a new paradigm in telescope technology, and will adopt a novel approach in order to meet the challenges of studying the earliest galaxies using red-shifted 21 cm radiation.

One problem faced by low frequency observations of atomic hydrogen during the reionisation era will be very bright radio emissions that originate from highly excited electrons in the Milky Way. This foreground radiation is approximately 10,000 times as bright as the faint cosmological signal that astronomers wish to study.

The challenge will be to remove this

bright foreground from the observations in order to reveal the distribution of atomic hydrogen during the reionisation era, so the MWA must be sufficiently sensitive that it can simultaneously measure both the brightness of the galactic foreground and the much fainter signal from the reionisation era. To achieve this, the MWA must obtain images using 21 cm radiation that have unprecedented quality.

A second problem is presented by the Earth's ionosphere, which at very low frequencies refracts the radiation causing a "shift" in the observed position of a radio-emitting source in the sky. This shift would not create a problem but for the fact that it is of a different size and direction in different regions of the sky as well as being variable in time!

If the MWA is to make a high-quality map of the sky using low frequency radio waves, then these ionosphere-induced distortions will have to be corrected. To perform this correction, the necessary strategy is again to obtain a very high quality image, with the additional demand that the image be obtained within the few minutes over which the ionosphere varies!

The requirement that very high quality images be produced rapidly is not compatible with traditional methods of radio astronomy, and therefore drives a novel design for the MWA. To see why, we must first understand how a radio astronomical image is made.

When making an image at radio wavelengths, astronomers generally employ a type of radio telescope known as an interferometer, which consists of a number (usually tens) of radio dish antennae. These arrays of dish antennae can be thought of as small parts of a giant imaginary mirror. If this array of dish antennae were rotated they would trace out all parts of the imaginary mirror, and so be able to make a good image.

However, radio interferometers are generally several or even hundreds of kilo-

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metres in extent, so they cannot be physically rotated. Rather, the Earth does the work for the interferometer by spinning once every 24 hours. The slow rotation of the Earth means that traditional methods will not work if an image must be made over a period of minutes.

A New Paradigm in Radio Telescope Design

The novel approach being adopted by the MWA is to construct an interferometer array that consists of a much larger number of antennae (hundreds rather than tens) than previous radio telescopes so that a good quality image can be observed within a short time without requiring the Earth's rotation. Of course, having a larger number of antennae comes with a cost, which is dominated by an enormous increase in the computing power required to process the observations.

In a radio interferometer, the different antennae are analogous to different areas on an optical telescope's mirror. In order to create an image, the signals from these different antennae need to be compared in a process known as "cross-correlation".

The number of calculations required is approximately the square of the number of antennae in the interferometer. So, by moving from tens of antennae to hundreds of antennae, the computing power required to make an image is increased by factors of hundreds or thousands. This poses a serious computing challenge that has only recently become feasible with the development of customisable computing hardware and parallel supercomputing.

The MWA will be constructed using 500 low-cost interferometer antenna "tiles". Each antenna tile is comprised of 16 receiving elements (dipoles) on a horizontal square grid (see Fig. 3).

Compared with the mechanically steerable dishes of traditional radio telescopes, the cost of each antenna for the MWA is low as it has no moving parts. Rather, the MWA will be "steered" electronically.

To understand how this works, consider



Figure 3. Antennae tiles making up the prototype MWA. Each tile consists of 16 cross-dipoles on a square grid. When complete, the full MWA will comprise 500 antenna tiles distributed over an area of diameter 1.5 km. The beam-forming box that will be used to electronically steer the array can be seen in the foreground. Image: David Herne, Curtin University

a source of radiation that is directly above the antenna tile. In this case all of the dipoles on the grid will receive the signal at the same time. However, if the source is off to one side, then the radiation will take slightly longer to reach the dipoles that are further from the source. Thus, the telescope can be pointed at different parts of the sky by making use of the small delay between the arrival times for radiation at different parts of the antenna.

A third serious problem for low frequency radio observations is posed by man-made radio-frequency interference. The frequency range of 100–200 MHz, at which the observations of atomic hydrogen during the reionisation era must be made, corresponds to the range of frequencies in which communication devices such as FM radios operate. This makes the detection of weak astronomical signals difficult when observing from sites near populated areas, since they must be separated from the strong terrestrial interference. Fortunately these man-made signals are variable in time and narrow in frequency, so they can be separated from the astronomical signal.

However, the MWA aims to circumvent the problem of radio frequency interference much more directly – by building the telescope on a remote site in central Western Australia. The Murchison Shire, situated inland from Geraldton, has an extremely low population density of around

one person per 1000 km². Together with favourable ionospheric conditions, the resulting lack of man-made radio signals makes Murchison Shire, which will also host the Australian Square Kilometer Array Pathfinder, one of the best sites in the world for radio astronomy.

A New Era for the Study of the First Galaxies

The formation of the first galaxies represents a very large gap in our understanding of the Universe's history. Until now, astronomers have not had the necessary observational tools to fill in this gap.

However, measurement of the reionisation era using the next generation of radio telescopes promises a new observational opportunity. The measurement requires novel approaches to radio astronomical observation, together with innovative technologies in order to meet the many new challenges. In constructing the MWA, Australian astronomers together with their Indian and US colleagues are at the forefront of this innovation.

When completed in 2010, the MWA, and complementary projects like the Low Frequency Array (LOFAR) in the Netherlands, will for the first time allow astronomers to begin answering the big questions regarding the earliest galaxies that formed in our Universe.

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