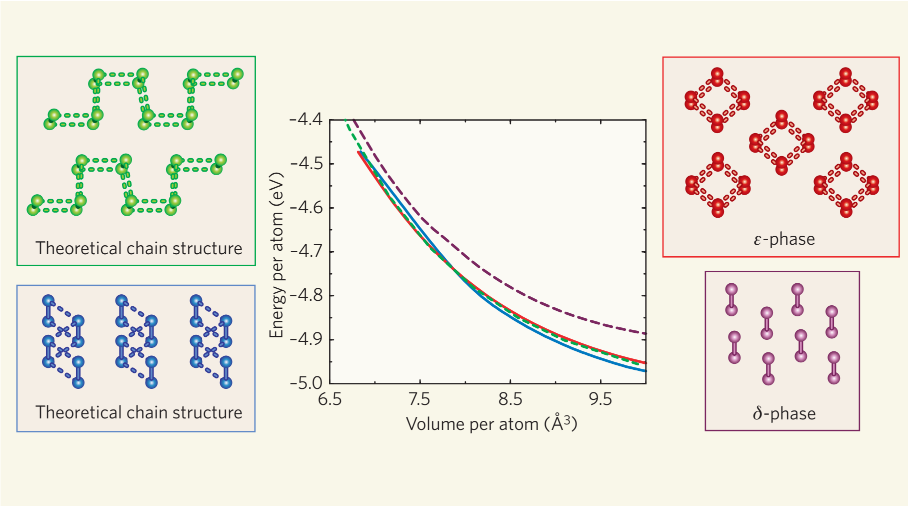

Figure 1 | Structures and energies of dense oxygen. These energy–volume curves for solid oxygen show the energies calculated for different arrangements of molecules at absolute zero. The calculations were performed using density functional theory and the projector augmented-wave method[15]. These calculations predict chain structures[9,11] (blue and green; dotted lines highlight pairs of molecules less than 2.2 Å apart) to be close in energy to the $(O_2)_4$ structure (red) that has now been observed in the ε-phase of solid oxygen[2,3]. The new $(O_2)_4$ structure is not the lowest-energy structure at this level of theory, demonstrating the need for additional studies. Another phase of oxygen, known as the δ-phase (purple), is shown for comparison, as an example of a layered structure[4].

from single-crystal diffraction has lower energy and is therefore more stable. Such calculations (Fig. 1) also show that the predicted $(O_2)_4$ structure is very close in energy to the chain-like structures that were previously proposed[9,11] for ε-oxygen. However, these calculations fail to show that the $(O_2)_4$ structure has the lowest energy, which is probably why previous theoretical attempts to predict the correct structure for ε-oxygen were unsuccessful. Notably, oxygen in an S_8-like ring structure is significantly higher in energy than all the known oxygen structures.

These results[2,3] will have broad relevance to other materials that are placed under extreme pressure. For example, as Lundegaard *et al.*[2] point out, there may be parallels between the behaviour of ε-oxygen and the charge-transfer activity observed in hydrogen at much higher pressure[12]. There is also experimental and theoretical evidence for clustering and formation of polyatomic phases in nitrogen under pressure[13,14]. The challenge now is to carry out structural and theoretical studies in the higher-pressure metallic and superconducting phases of oxygen. As another character in *Oxygen*[1] opines, without the discovery of oxygen there would be "no chemistry as we now know it". The findings with ε-oxygen open up a fresh dimension of chemistry that we are only just getting to know. ■

Burkhard Militzer and Russell J. Hemley are in the Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Road NW, Washington, Washington DC 20015, USA.
e-mails: militzer@gl.ciw.edu; r.hemley@gl.ciw.edu

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ASTRONOMY

Dawn after the dark age

Richard McMahon

The latest surveys provide evidence for one, maybe two, galaxies farther back in cosmic time than ever detected before. But does the fact that we don't see more mean these are the very first galaxies to be formed?

Determining when the first stars and galaxies formed is a matter of profound importance: fuelled by primordial hydrogen, these bodies triggered the nucleosynthesis of the heavier elements, such as carbon, nitrogen and oxygen, that are the basis of life. By studying the first galaxies, we can also hope to understand how the Universe formed and evolved, and detect the younger progenitors of galaxies like our own Milky Way. In this issue, Iye *et al.* (page 186)[1] report the discovery of the most distant galaxy yet, one whose photons must have left it 12.7 billion years ago, when the Universe was just 750 million years old, and some 8 billion years before the Sun and Earth were formed. And Bouwens and Illingworth (page 189)[2] report on their search for galaxies even farther away, more than 13 billion light years from Earth.

The study of the most distant galaxies has much in common with archaeology: the farther back one looks, the scantier the evidence becomes, and the harder it is to draw conclusions. Two factors are responsible. First, there are the immense distances of around 10^{24} km implied by light journey times of more than 10 billion years; the brightness of a source diminishes with the inverse square of its distance. Second, there is the expansion of the Universe, which stretches the wavelength of light from distant objects by a factor $1 + z$. The quantity z is known as the redshift, as the expansion moves all observed wavelengths towards longer, redder wavelengths. The older an object is, the greater its redshift; but unfortunately, the redder one gets, the brighter the night sky becomes. As a result, searching for the very earliest objects becomes — from the ground, at least — increasingly difficult.

Like archaeology, astronomy also has its Dark Ages from which evidence is particularly sparse. As the Universe expanded and cooled, neutral hydrogen and helium were created from the hot plasma of matter at the so-called epoch of recombination, around 400,000 years after the Big Bang. As very few atoms remained ionized in this neutral Universe, very little radiation can be detected from this era. The

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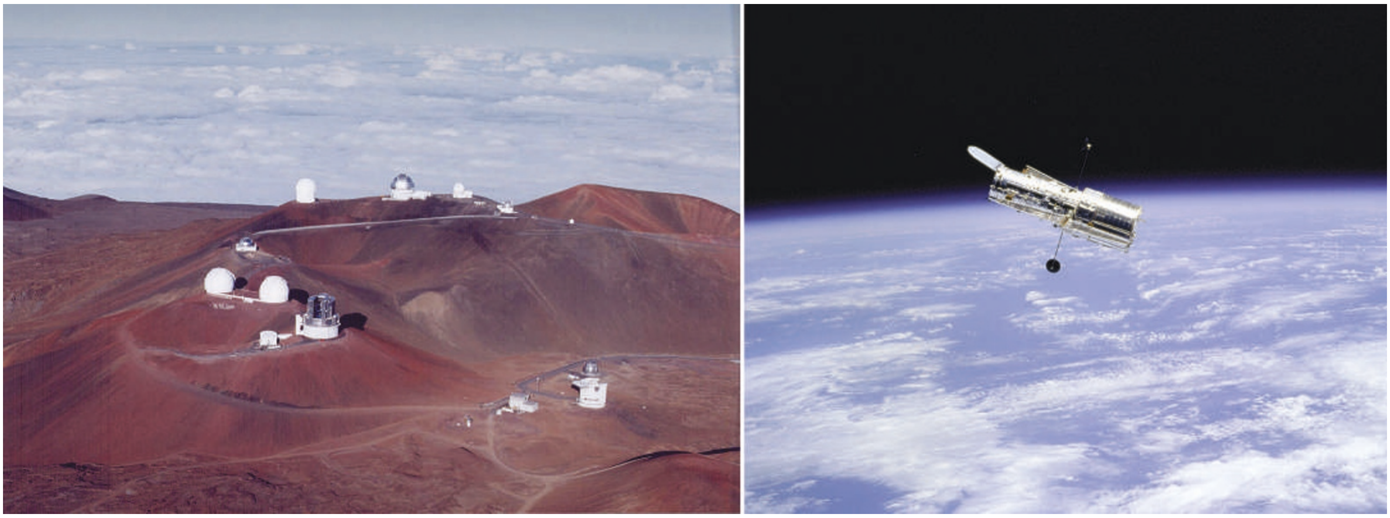

Figure 1 | On Earth as it is in heaven. **The Subaru and Hubble Space telescopes, used by Iye *et al.*[1] and by Bouwens and Illingworth[2] in their respective studies of early galaxies, overlook the clouds — the one some 4 km up on the summit of Mauna Kea on Hawaii, the other from orbit at an altitude of around 600 km over Earth's surface.**

situation changed only when the first generation of luminous sources — massive stars, galaxies and accreting black holes — reionized and 'lit up' the gas in the Universe.

In recent years, the search for galaxies has been pushed back progressively towards these trailblazers. Improvements in solid-state detector technology have followed Moore's law, with a doubling of chip density every two years or so; mega-pixel devices and highly efficient, large-format red-sensitive detectors have arrived on wide-field imaging instruments, on a new generation of 8-metre-aperture telescopes, and on the refurbished Hubble Space Telescope (HST). From a redshift of 4.55 in 1996 (ref. 3), the earliest star-forming galaxy had been put back to $z = 6.56$ by 2002 (ref. 4).

Iye and colleagues' discovery[1] takes us farther back to $z = 6.96$. But the authors note that, by comparison with observations at smaller redshifts, they would have expected to find around five galaxies in a survey of their scale. Bouwens and Illingworth[2] recount a similar story at redshifts of 7–8. Where they might by extrapolation have expected to find around ten galaxies, they found only one unconfirmed candidate. So could we now really be looking back to the very earliest phase of galaxy formation at the epoch of reionization? With the current results it is still hard to tell.

The two surveys[1,2] employed quite different experimental approaches. Iye *et al.*[1] used the 8.2-m-aperture Subaru telescope on Hawaii (Fig. 1), one of the largest ground-based telescopes, together a mosaic of CCD detectors with a total of 84 million pixels. The authors exploited a gap in the intense hydroxyl airglow radiation that is created by processes high in Earth's atmosphere and dominates the terrestrial night sky at wavelengths above 700 nm. Using a special interference filter centred on 975.5 nm with a bandwidth of 20 nm, they could search between hydroxyl lines for so-called Lyman-α radiation. This unique, asymmetric spectral signature is typical of star formation, and comes from photons produced by a ground-state transition in hydrogen. In this case[1], the focus was on an ultraviolet wavelength of 121.6 nm. At redshift 6.96, the observed wavelength is stretched by a factor of 7.96. The resulting radiation at 968.2 nm is beyond the range of the human eye, and almost at the limit of conventional silicon-based CCD detectors. Even so, we can expect this ground-based technique to be extended to longer wavelengths in the coming years[5].

Bouwens and Illingworth's identification method[2] used the 2.5-m-aperture HST (Fig. 1). As this is above Earth's atmosphere, it is not affected by airglow radiation effects and can work at longer wavelengths (and so higher redshift). The authors looked for a break in the radiation between the infrared and the optical regions that is caused by absorption through neutral hydrogen along the line of sight, and found this in one case. Unlike the characteristic Lyman-α emission, this break is not an unambiguous signal of a high-redshift galaxy with high rates of star formation, but could have been caused by interstellar dust or intrinsic stellar features in galaxies at lower redshifts. For this reason, independent spectroscopic confirmation is required for the existence of this galaxy. As the HST does not carry appropriate instrumentation, this might have to await the launch, currently projected for 2013, of Hubble's successor, the 6-m-aperture James Webb Space Telescope.

Although they could search at longer wavelengths, the smaller aperture and older detectors on the HST meant that Bouwens and Illingworth's observations[2] were confined to a patch of sky about 50 times smaller that that covered by Iye and colleagues' optical detectors[1]. Whereas the Subaru telescope needed just a few nights to collect the requisite data, the HST needed a few years. That also limits the scope for extending the HST work to larger areas of sky within the few remaining years of the telescope's projected lifetime. In the shorter term, Iye and colleagues plan to search another patch of sky to increase their sample size. Only then will the presence, or absence, of further galaxies be able to tell us whether we really are homing in on the era of reionization.

Other techniques exist to search for galaxies at higher redshifts. A candidate galaxy at $z = 7$ has been reported using gravitational lensing — the bending of light by massive intervening bodies — to amplify images of distant objects that would otherwise be undetectable[6], although airglow has prevented spectroscopic confirmation of this galaxy, too. Indirect evidence for galaxies at still higher redshifts comes from recent observations by NASA's WMAP satellite of polarization in the cosmic microwave background radiation, which was left behind at the epoch of recombination. A galaxy spotted at $z = 6$ might have formed its first stars at up to $z = 13.5$ — just 300 million years after the Big Bang[7].

The success of Iye *et al.*[1] bodes well for continued searches for the first galaxies to emerge from the Universe's dark ages. Bouwens and Illingworth's conclusions[2] are no less important, reminding us just how difficult this task might be. Armed with both sets of results, we can design better experiments to increase the probability that still older galaxies can be discovered. ■

Richard McMahon is at the Institute of Astronomy, University of Cambridge, Cambridge CB3 OHA, UK.
e-mail: rgm@ast.cam.ac.uk

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