TEACHER NOTES – ASTRONOMY IN THE NEWS #06

FIRST STARS IN THE UNIVERSE

Slide 2 – Background Science: The Big Bang and redshift

After the Big Bang, the first stars did not form for millions of years. The first detection of light after the Big Bang is the cosmic microwave background radiation, which occurred at approximately 379,000 years after the Big Bang. This occurred when the hot plasma and radiation from the Big Bang cooled sufficiently that protons and electrons could combine to form hydrogen.

However, the first stars did not form until a much later time into the Universe. The time at which this occurred is referred to as the 'cosmic dawn' and is thought to have occurred a few hundred million years after the Big Bang. There are hints at when this would have occurred from both simulations and observations. Simulations of dark matter halos show that accumulations large enough to form galaxies that could spark star formation could occur at 150-250 Myr (million years) after the Big Bang, or at a redshift of z = 15-20.

Observations are also consistent with this age range. The ultraviolet emission of stars should alter the emission of the neutral hydrogen. The gas formed after the Big Bang will be cooling, and concentrations of it will absorb the light emitted from the Big Bang. However, once stars form, they will begin to heat the gas. Then stars die, especially the first stars which were massive, leaving neutron stars and blackholes. The x-ray radiation from these objects will further heat the gas. Eventually, the gas will become hotter than the background and a spectrum of neutral hydrogen gas across redshift should show emission prior to the formation of stars, absorption at the redshifts associated with the first generation of stars, and then emission once it becomes warmer than the background. The range for the accumulation of gas, then the heating of the gas because of stars is in the redshift range z = 16-19.

Observations of individual galaxies (i.e. the output of the stars in the galaxy) can be converted to redshifts by observing two sets of hydrogen lines, the Lyman series and the Balmer series. These lines are prevalent in stellar objects due to the high abundance of hydrogen in the Universe. They are caused by the transition of an electron from a higher energy level to either the first (Lyman) or second (Balmer). There is a break in the spectrum which is caused once an electron completely leaves the hydrogen atom, thus causing a hydrogen ion and these breaks occur at the wavelengths quoted below. The observed wavelengths can be converted to redshifts using the standard redshift formula:

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$

Where z is the measured redshift, λ_{obs} is the observed wavelength and λ_{emit} is the emitted wavelength (i.e. the theoretical wavelength).

IMAGES:

1. (Top left) Cartoon of the time evolution and stages after the Big Bang. The important points for this bulletin are the cosmic background radiation at 380,000 years and the first stars and galaxies at 200 million years.
2. (Top right) Spectrum of atomic hydrogen emission across cosmic time. The dip is the absorption feature that is caused by the gas accumulating, whilst the spectrum shows a sharp increase to emission at z=15-16 when stars have formed and their radiation, along with the radiation of their remnants, has heated the gas to be warmer than the background emission.
3. (Bottom) Example of a galaxy spectrum in the optical and near-infrared. This example spectrum shows a galaxy at z=7, where the Hubble Space Telescope can observe the Lyman break, whilst Spitzer can observed the Balmer break. The Lyman break usually occurs at 912 Å (912 Angstroms, or 91.2nm at ultraviolet wavelengths), whilst the Balmer break occurs at 3646 Å, which is also ultraviolet. However, as you'll see in this spectrum, these features are redshifted to 1 and 3 µm.

Slide 3: The first stars in the Universe

The further back in the Universe a galaxy was formed (higher redshifts), the longer the wavelengths that the Lyman and Balmer breaks occur at. The Hubble Space Telescope and Spitzer Space Telescope allow for the breaks to be observed in the optical and near-infrared wavelengths, which correspond to redshifts of z = 9-11. At that point, the Universe was less than 600 Myr old, so main sequence stars older than 250 Myr would imply star formation before z = 14.

A sample of galaxies were selected that would fit the criteria of having redshifts 9-11 with a significant population of main sequence stars. They were selected so that they were sufficiently dim, had no significant detections at wavelengths shorter than the Lyman break, at least two significant detections at wavelengths longer than the Lyman break and a redshift consistent with $z > 9$. A further criterion was applied, which was an indicator of the Balmer break. This was calculated as 3.6 µm – 4.5 µm > 0.5. This difference would imply the jump in flux evident at the Balmer break.

By using these criteria, 6 galaxies were found. The redshifts were then estimated in two ways, photometrically and spectroscopically. Photometric redshifts are calculated by fitting a model spectral energy distribution (or spectra) to the measured points. This fit would then reveal the wavelengths at which the Lyman and Balmer breaks would be found. There is a large uncertainty in this method. Spectroscopic redshifts require detecting a known line in a spectrum, in this case Lyman-α (this is where the electron drops from the second energy level to the ground state). The wavelength that this line is found at can then be compared to the laboratory derived value at rest frame. This is a much more precise method. From the sample of 6 galaxies, 3 (and maybe 4) had redshifts consistent with star-formation contributions past z = 10, with at least 39% of the star formation occurring in those galaxies before that time.

The exciting result is that a sample (albeit small) of these early galaxies are found, and by looking at the sensitivities of instruments on the next generation space telescope, the James Webb Space Telescope, we should be able to observe many more of these and constrain the exact age that star formation started in the Universe.

The articles that this resource are built off can be found here:

https://www.bbc.co.uk/news/science-environment-57515422

https://www.theguardian.com/science/2021/jun/24/cosmic-dawn-scientists-hope-peer-back-time-see-birth-stars

A free version of the research article can be found here:

https://arxiv.org/abs/2104.08168

IMAGES:

1. (Top left) Spitzer image at 4.5 μm of one of the six galaxies in the candidate high-redshift star-forming galaxies. This image is to show how hard it is to detect these galaxies as even using space telescopes, they are very pixelated and only a handful of pixels across.
2. (Top right) These are the measurements of redshift for one of the galaxies in the sample. The two methods are both shown, photometric on the left, spectroscopic on the right. The photometric method shows the observed fluxes at particular wavelengths in blue, with the model spectral energy distribution fit to these data, and the associated predicted fluxes in red. The insets show the predicted stellar mass in the galaxy (left) and the distributions of possible redshifts from the derived model (right). The spectroscopic method shows the observed spectrum of light from the red circles show the detected emission of the Lyman-α line, with the associated line highlighted in yellow in the spectrum.
3. (Bottom left) The best model spectral energy distribution fits have the power to predict the flux that should be observed in a particular line at different redshifts, in this case the 1500 Å line, which is a predictor of star-formation rate. The star-formation rate is the mass of stars per year that a system forms. By looking at these predicted line strengths, and comparing them to the different instruments and filters on the James Webb Space Telescope, we may be able to observe a large sample of galaxies which are forming stars at redshifts of z = 12-14, even to z = 16 for some galaxies.
4. (Bottom right) Artist's impression of the James Webb Space Telescope which is expected to be launched in November 2021.

Slide 4 – Activity: Calculating redshifts

Can you calculate the redshift of the three galaxies with significant star formation prior to redshift z = 10? The table on the slide gives the wavelength of the observed Lyman-α line of these galaxies. Using the formula given, and the rest frame wavelength of the Lyman-α line, calculate the redshift of the galaxies. The answers for the three galaxies are shown below:

Galaxy Name	Redshift
MACS0416-JD	9.28
MACS1149-JD1	9.11
GN-z10-3	8.78

GCSE Specifications:

Specification	Knowledge Point
Pearson Edexcel Astronomy	13.21, 16.1, 16.2
Pearson Edexcel Physics	5.3, 6.7, 6.8, 7.9, 7.12, 7.19
Pearson Edexcel Combined Science	6.7, 6.8
OCR Physics B	1.1.6, 1.1.7, 6.5.7
OCR Combined Science B	1.1.6, 1.1.7
AQA Physics	4.4.1.1, 4.6.2.1, 4.6.2.6, 4.8.2
AQA Combined Physics	4.4.1.1, 6.6.2.1, 6.6.2.6

A-Level Physics Specifications:

Specification	Knowledge Point
Pearson Edexcel	96
OCR Physics A	5.5.2 (a,c,e), 5.5.3 (f,h,n)
OCR Physics B	3.1.1 (a), 5.1.3 (a), 6.2.1 (a)
AQA Physics	3.2.2.3, 3.9.3.1