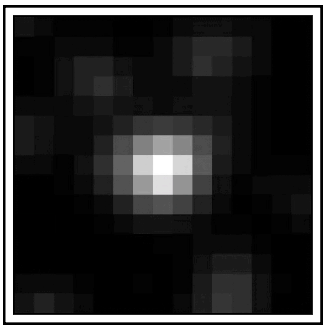

Ancient Light

Dr Steve Barrett

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The Universe is vast and ancient. Large telescopes such as the Hubble Space Telescope have imaged galaxies that are billions of light-years distant. It is easy to assume that any instrument that is capable of detecting the light from such distant galaxies must be very sophisticated and very expensive, with a price tag as astronomical as the distances involved. In this article I show that this is not so by demonstrating that an ordinary camera designed to take photographs in daylight can be used to capture the light from a galaxy that is so distant from us that the light it emitted had been travelling for most of the age of the Universe to reach us.

Throughout 2020 the coronavirus pandemic tended to make people look down at their feet to follow the social-distancing instruction stickers scattered over pavements and floors. Despite this, I found that Professor Stephen Hawking's words still resonated: "Remember to look up at the stars and not down at your feet". So I set myself a lockdown challenge – not just to look up, but to look up as far as possible. What is the most distant object that I can photograph with my camera *without* using a telescope?

I looked up a research paper [1] cataloguing very distant galaxies (quasars) that emit a huge amount of energy and picked the most distant one that is high in the sky as seen from the UK during the summer months. Having identified the target quasar [2] the first opportunity to try to image it came on the night of 20 July. My camera equipment comprises a Nikon D7500 digital SLR camera with a 300 mm f/4 telephoto lens. This is the camera and lens that I use for normal daylight photography – they are not 'customised' or 'modified' in any way for astrophotography. I set up the camera on a small star tracker that rotates the camera at 1 revolution/day to follow the stars, as shown in Figure 1. A star tracker can be built as a DIY project [3] or they are available commercially from various manufacturers.

Figure 1. Nikon camera and lens on an iOptron SkyTracker (white box). The tracker rotates the camera at 1 rev/day and so, providing that the tracker is aligned parallel to the Earth's axis using the small polar alignment scope, the camera will follow the stars.

The quasar's location in the sky, given by its celestial coordinates [2], is in the constellation of Draco (Figure 2) which is high in the sky during the darkest part of the night in the UK spring/summer.

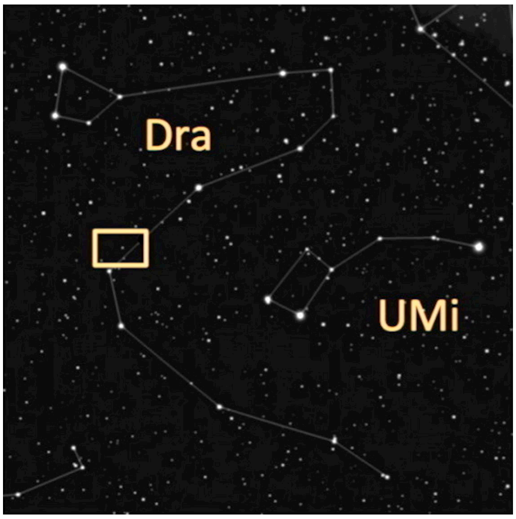


Figure 2. The constellations of Draco and Ursa Minor, showing the rectangular field of view of the 300 mm lens. The small dot in the centre of the rectangle is the fifth-magnitude star AT Dra.

Not knowing how long was necessary, I exposed for as long as the short summer night allowed. Rather than take a single very long exposure, I took a continuous series of shorter 30-second exposures over a period of about an hour either side of midnight. After discarding some of the images that were spoiled by passing clouds, the remaining exposures were added together by computer software that ensured that all the the stars were in the same position in each image, producing a resultant image that was equivalent to taking a single two-hour-long exposure. The final image, the result of adding together 256 exposures of 30 seconds each, is shown in Figure 3.

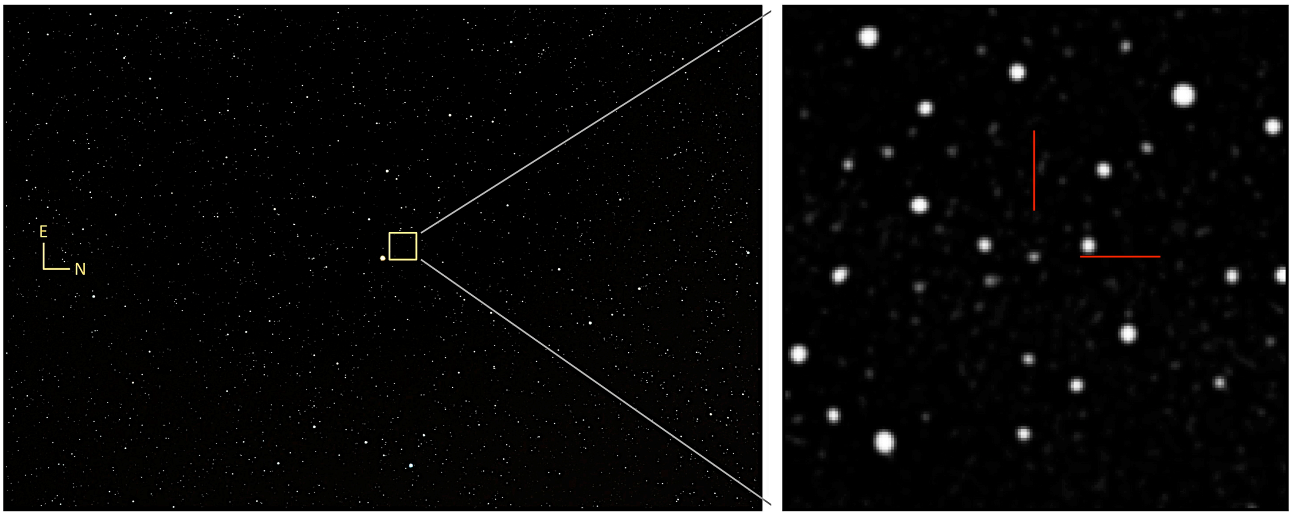


Figure 3. The full field of view of the 300 mm lens in a 2-hour exposure. The small square shows the area covered by Figure 4.

Figure 4. Zooming in to the region adjacent to the star AT Dra shows the quasar indicated by the two red lines.

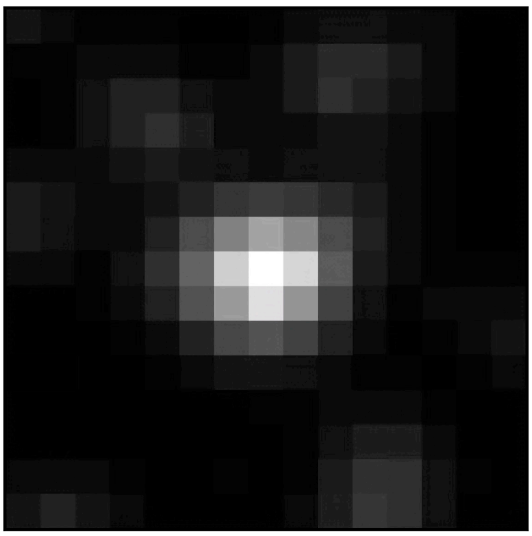


Figure 5. Zooming in still further shows that most of the light from the quasar is focussed into just one pixel of the 20 megapixel image.

Figures 4 and 5 show greater magnification of the central region of the image, demonstrating that the quasar has been imaged successfully. As a double-check, astrometric solving (aka plate solving) the image shown in Figure 4 confirmed that the celestial coordinates of the central object match precisely those of the quasar.

Figure 6 shows that the small section of the full image, covering about 0.1° x 0.1° of sky, has captured 10 galaxies in addition to the quasar itself. These galaxies cannot be distinguished by eye as most of them are so distant that they look very similar to the (much closer) stars in our Milky Way galaxy – identifying these objects as galaxies can only be achieved by comparing the image with archive images of the same patch of sky taken by professional research telescopes. If the number of galaxies found in this small section is typical of the whole image, covering 4.5° x 3° of sky, then it may have captured as many as 7000 galaxies in total. It is sobering to realise that this is comparable to the number of galaxies captured by the Hubble Space Telescope in the iconic Hubble Deep Field images.

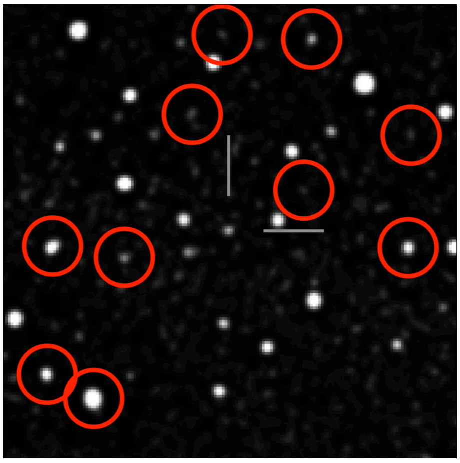


Figure 6. This small section of the full image covers a little more than 0.1° x 0.1° of sky and has captured 10 galaxies (circled) in addition to the quasar itself.

Having shown that it is possible to capture the light from this quasar using a digital SLR camera, the big question is ... just how far away is it? If the quasar is just a tiny dot, even in a large telescope, how can its distance be determined? We have to remind ourselves that the distance to the quasar cannot be measured. The length of time that the light has been travelling to reach us also cannot be measured. The key to determining distances on cosmological scales is the one thing that *can* be measured – the spectrum of the light formed by measuring the light intensity as a function of its wavelength (or colour). The spectrum of light emitted by an object that is moving relative to us will exhibit features (peaks or troughs in the light intensity) that do not appear at the same wavelengths as they would if the light source was not moving relative to us. Objects moving away from us have their spectral features shifted to longer (redder) wavelengths and so this is called a redshift. The redshift is quantified by dividing the shift in wavelength by the wavelength expected for a stationary light source, and the resultant number is given the symbol z. Figure 7 shows the visible spectrum for the quasar, from wavelengths of 4000 Å (blue) to 7000 Å (red). The largest feature in the spectrum has been identified as being redshifted from about 1200 Å, in the ultraviolet part of the spectrum, to 6500 Å due to the high recession speed of the quasar. The shift (6500 Å – 1200 Å) divided by unshifted value (1200 Å) is equal to 4.3, so this quasar has a redshift of z = 4.3.

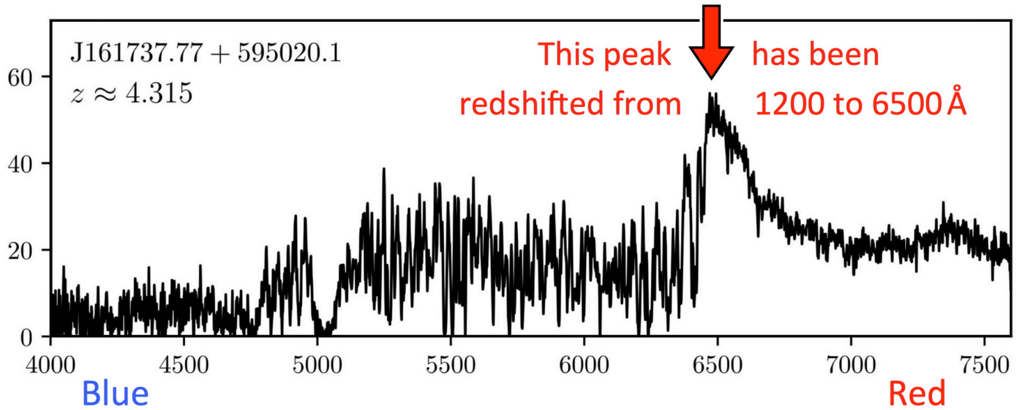


Figure 7. The spectrum of the quasar from wavelengths of 4000 Å (blue) to 7000 Å (red). The large peak has been redshifted from 1200 Å, beyond the left end of this spectrum, to 6500 Å as a result of the quasar receding from us faster than the speed of light. Figure adapted from Reference [1].

Determining the distance to the quasar is complicated by the fact that the Universe is continuously expanding, and so the distance between any two objects keeps changing. Not only that, but the expansion rate itself changes with time. This means that we can only calculate the distance to a remote object if we have some understanding of how the Universe is expanding, and in particular how the Universe has expanded over the time interval between the time when the light left the object (perhaps billions of years ago) up to the time when it arrived here on Earth (now). The so-called concordance model of the Universe is based on the currently accepted 'best guess' of the parameters that determine the way that the Universe expands and evolves [4]. Using these parameters it is possible to convert measurements of redshift into distances and these are shown in Figure 8 for redshift values between z = 0 and z = 6. For every value of redshift, three distances can be calculated: (i) the distance to the object when the light was emitted (blue line); (ii) the distance that the light has travelled to reach us (green line); and (iii) the distance to the object now (red line). For small values of the redshift these three distances are essentially the same, but for larger redshifts they differ substantially because the Universe expands by a significant amount in the time it takes the light to travel from the object to us.

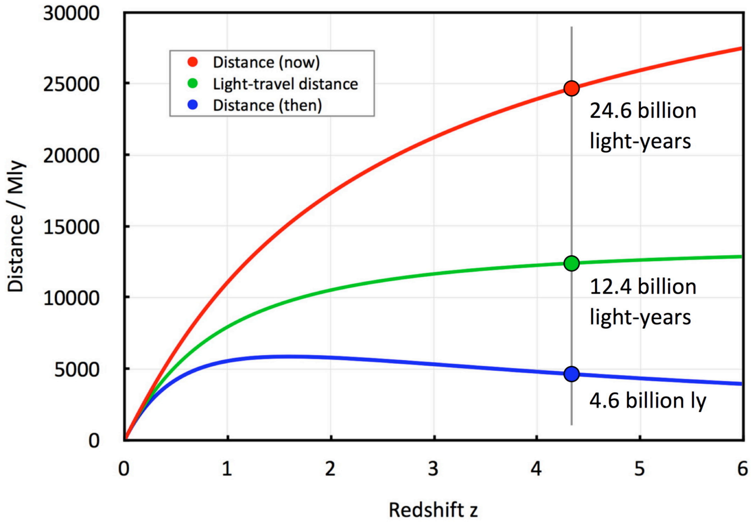


Figure 8. Converting redshift to distance depends on models of how we think the Universe has expanded over the billions of years that the light has taken to reach us. The distance to the object when the light was emitted (blue), the distance that the light has travelled to reach us (green) and the distance to the object now (red) are shown as a function of redshift z. The values are given for the quasar at z = 4.3.

Taking the distances calculated for our quasar with a redshift of z = 4.3 we find that the quasar was about 5 billion light-years away when the light was emitted; the light from the quasar has been travelling for over 12 billion years; while the light was travelling the Universe continued to expand and so the quasar is now about 25 billion light-years away. The light-travel time, also known as the look-back time, of over 12 billion years is absolutely mind-boggling. Bearing in mind that no telescope, no matter how powerful, can look back further than 13.8 billion years (the age of the Universe) it is remarkable to realise that a camera can 'see' light that has been travelling for 90% of the age of the Universe.

A quick back-of-the-envelope calculation using the distances quoted above leads to a very interesting conclusion. The distance to the quasar increased by 20 billion light-years during the light-travel time of 12 billion years, so that corresponds to the quasar receding from us at a speed that is *faster* than the speed of light. At first sight this seems wrong, but actually this does not contradict any laws of physics. The quasar is not moving through space at this speed, but the Universe is expanding at this rate and the quasar is 'along for the ride'. A more detailed calculation tells us that when the light was emitted, the quasar was receding from us at a little more than twice the speed of light and is now receding at a little less than that, as shown in Figure 9.

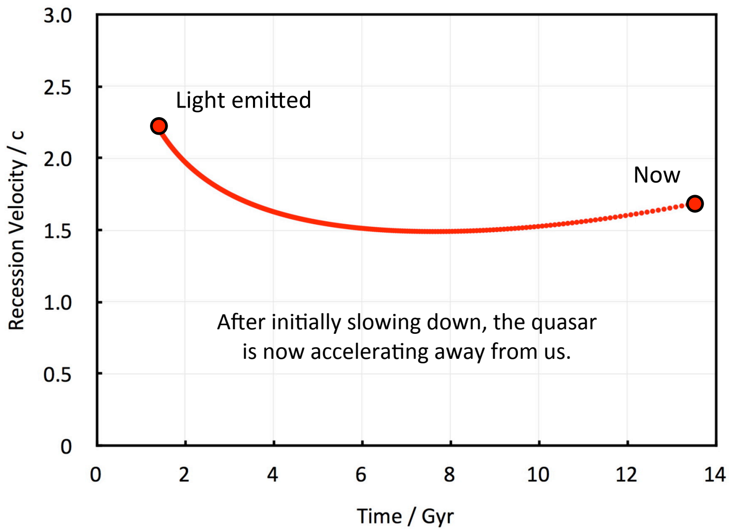
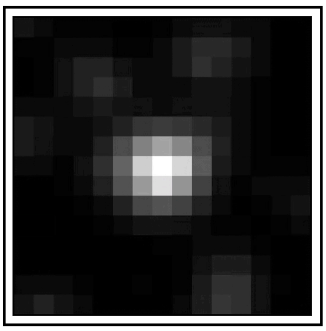


Figure 9. The recession velocity of the quasar as a function of time. When the light was emitted by the quasar (1.4 billion years after the Big Bang) it was receding from us at $v = 2.2\,c$. After initially slowing down, the quasar is now receding at $v = 1.7\,c$ and accelerating away from us.

When looking at the image of the quasar, I think about the incredible journey that the ancient light has taken to form the image, with the narrative as seen from the perspective of the light ...

> *The light was emitted by the quasar 1.4 billion years after the Universe was created in the Big Bang.*
>
> *For the first 2 billion years of its journey the light was dragged backwards by the Universe expanding faster than the speed of light. Throughout this time, the light made no headway towards us.*
>
> *Eventually, it started to close the distance to us.*
>
> *It had already been travelling for nearly 8 billion years when the Sun and the Earth were born. The light continued on its journey through the void for another 4.5 billion years.*
>
> *Life evolved on Earth. The light travelled on.*
>
> *Dinosaurs came and went. The light travelled on.*
>
> *In the last million years of its journey it arrived at the edge of our Milky Way galaxy, crossed a few spiral arms, and entered the Solar System.*
>
> *In its last few hours it finally arrived at Earth, travelled through the atmosphere in a fraction of a second, hurtled towards England, dodged a few clouds, entered the lens and hit the camera sensor.*

Just a pixel in the image ...



... but what a journey!

References

[1] Extremely Luminous Quasar Survey in the Pan-STARRS 1 Footprint (PS-ELQS)
J-T Schindler et al, *Astrophys. J. Suppl. S.*, 243 (2019) 5
https://doi.org/10.3847/1538-4365/ab20d0

[2] Quasar PS1 J161737+595020, magnitude 17.4, redshift z = 4.315

[3] https://www.liverpool.ac.uk/~sdb/Astro/K2/K2-flyer.pdf

[4] Matter density = 0.3, Dark Energy density = 0.7, Hubble constant H_0 = 70 km/s/Mpc

S.D.Barrett@liverpool.ac.uk

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