The Discovery of Quasars[1]

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THE DISCOVERY OF QUASARS was a gradual process that took several years, from 1960 to 1963, and was eventually resolved through the discovery of their redshifts. I will first mention the essential role that radio astronomy played in finding these objects and then describe the optical work that led to the discovery.

Radio astronomy found its roots during World War II, when radar reflections had occasionally shown interference from unknown outside sources. After the war, radio astronomy observatories were set up at Jodrell Bank and Cambridge in the U.K. and in Australia. A number of discrete radio sources were soon discovered. The *Revised 3C Catalogue of Radio Sources* (3CR) provided positions and intensities for many sources accessible from the Northern Hemisphere. At Caltech's Owens Valley Radio Observatory, an interferometer of two 90-foot radio dishes was employed by Thomas Matthews and his collaborators in the late 1950s to produce more accurate positions of 3C sources. He would prepare optical observing charts in which the radio position was indicated on a photographic image of the sky. An optical observer could then take a spectrum of one or more objects near the radio position and confirm the identification on the basis of the spectrum. Initially, all strong radio sources were identified with galaxies of the elliptical type, most of them with emission lines in their spectra.

Galaxies are large stellar systems, like our own Milky Way Galaxy and the nearby Andromeda Galaxy. These building blocks of the Universe typically contain 100 billion stars, and much dark matter of unknown nature. The total number of galaxies is likely of the order of 100 billion. The velocities of galaxies are all directed away from us, leading to a redshift in their spectra. As shown by Lemaître in 1927 and confirmed by Hubble in 1929, the redshifts of galaxies are proportional to their distances, leading to the concept of the expanding Universe.

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With the currently accepted scale length, the Universe started from a very small volume (the big bang) around 14 billion years ago.

The situation changed in 1960 when Matthews attempted to identify the radio source 3C 48. Rather than a galaxy, he found at the radio position a 16th mag star. Observations carried out by Sandage and by Greenstein showed that the star was surrounded by weak nebulosity and had a spectrum showing three prominent emission lines with several weaker ones. The lines could not be identified.

Matthews and Sandage submitted a manuscript about 3C 48 to the *Astrophysical Journal* two years later. They showed from extended optical photometry that it varied by about 30% in a year. In the article, they say of the three strong emission lines that they are "not a plausible combination of redshifted emission lines." Assuming that the object was in our Galaxy, they estimated that 3C 48 was at a distance of around 100 pc or 300 light years with considerable uncertainty.

I had not been involved in any of the observations of 3C 48. I started to work with Matthews on the identification of radio sources in 1961, taking spectra of the optical candidates using the Palomar 200-inch telescope. Most of the candidates were galaxies, but we did identify three radio sources with optical stars, like 3C 48 but much fainter. Their spectra showed very few emission lines, each at a wavelength different from those in 3C 48, and none of them could be identified. It was the next stellar object, 3C 273, that was to provide the clue to the mystery of these star-like radio sources.

The strong radio source 3C 273 had attracted the attention of Australian radio astronomers, since it would be occulted several times by the Moon in 1962. The times of disappearance and reappearance of the source would give more accurate information about the position than was otherwise possible at the time. Cyril Hazard carried out the observations at the Parkes 210-foot radio telescope.

The occultation observations were successful and showed that 3C 273 was a double source with a separation of about 20 arcseconds. Component A had a steep radio spectrum and was extended, while B had a flat spectrum with most of the radiation from a diameter of less than an arcsecond. Tom Matthews gave me the finding chart based on the occultation positions. A bright star of magnitude 13 was seen near component B. Component A was located at the end of a very faint optical jet.

I made the first spectroscopic observations of 3C 273 at the Palomar 200-inch telescope in December 1962. These observations were carried out in the prime focus cage of the 200-inch telescope, inside and near the top of the telescope. The cage had a chair mounted in a way that allowed the observer to stay more or less horizontal as the

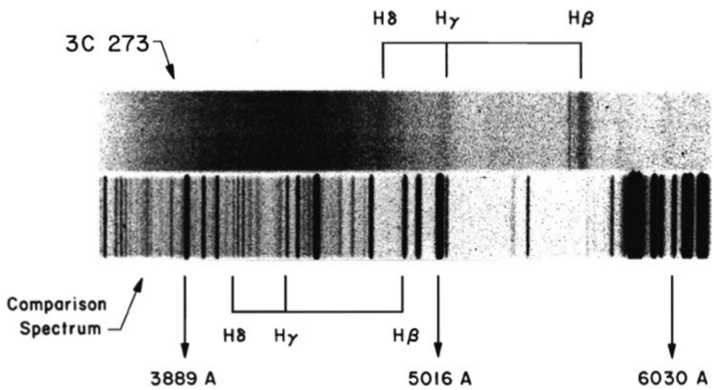

FIGURE 1. The lower spectrum shows emission lines of hydrogen, helium, and neon that provide the wavelength scale, from blue to red. The upper spectrum is that of the bright "star," widened to improve the visibility of its emission lines. In the comparison spectrum three lines of the Balmer series of hydrogen lines are indicated. They also show in the 3C 273 spectrum, but at wavelengths 16% larger than in the comparison. This signifies that the light of 3C 273 has a redshift of 0.16. Two further lines not shown in this spectrum confirmed this redshift. The narrow line just left of Hβ in the 3C 273 spectrum originates in the Earth's atmosphere.

telescope swung across the sky. The focus of the telescope was right in front of and below the observer. The nebular spectrograph was mounted on top of it with a camera. The camera had to be loaded in the dark with a small plateholder with a photographic plate of about 25 × 15 mm. Exposure times tended to be very long since the quantum efficiency of the photographic plates was very low and typically only a few objects could be observed each night.

On 27 December 1962 I observed the bright stellar object in 3C 273. Since it was more than a hundred times brighter than the typical objects I observed, it was difficult to estimate the best exposure time. The spectrum was strongly overexposed, but my notes show that it did have a broad emission line in the ultraviolet; also broad emission at 5650 A. I took a spectrum at twice the spectral dispersion on 29 December. This was successful: I noted four broad emission lines and a number of possible ones.

When Hazard heard that we had identified 3C 273, he suggested that I write a letter to *Nature* to accompany one that he had written. It was in the process of writing that letter that I discovered the redshift.

It happened on 6 February 1963. While I was writing a draft, I decided to have another look at the spectra. While I was doing so, it struck me that if I ignored the strong ultraviolet line and a very weak line, the four remaining ones showed increasing spacing and increasing intensity from blue to red. For reasons that I don't remember I tried to construct an energy-level diagram. When the energy levels did not come out regularly spaced, I was annoyed because they had to be. To check on the regularity of the observed lines, I decided to compare them with the Balmer lines of hydrogen, which are very regular. Specifically, I took for each line in 3C 273 the ratio of its wavelength over the wavelength of the nearest Balmer line. The first ratio was 1.16, the second was . . . also 1.16. It suddenly struck me that I might be seeing a redshift. When the third and fourth ratios were also close to 1.16, it was abundantly clear that I was seeing in 3C 273 a redshifted Balmer spectrum. An emission line that had been observed by J. B. Oke in the red at 7590 A, could now be identified as the Balmer H-alpha line. Correcting the wavelength of the ultraviolet line in 3C 273 for the redshift, it could be identified as MgII emission.

I asked Jesse Greenstein to come to my office. He produced the list of emission lines observed in 3C 48. It did not take us long to find a redshift of around 0.37, mostly based on forbidden lines. With this redshift, the strongest line turned out to be the same MgII emission that I had just found in 3C 273. There was no doubt that these two stellar objects had large redshifts!

It was a stunning development. The most obvious explanation of a large redshift is that it is a consequence of the expanding Universe, just as seen for galaxies. Hubble's law states that the expansion velocity is proportional to the distance, at a rate of 21 km/sec for each 1 million light years. With 3C 273 moving away at 47,000 km/sec, this translates into a distance of 2 billion light years. At this distance, 3C 273 would have to be 100 times more luminous than the typical galaxy.

The situation for 3C 48 was as follows. Its redshift of 0.37 corresponded to a distance of 4 billion light years. Sandage's observations had shown that 3C 48 was varying by about 30% in a year. So the light source could not be much bigger than 3 light years, whereas typical galaxies have sizes of at least 10,000 light years. Were we really prepared to propose that an object looking like a star could have the luminosity of 100 galaxies, yet be 3,000 times smaller in diameter?

We did investigate the possibility that the redshift was gravitational, but quickly dismissed it on the basis of spectroscopic arguments. So we accepted the redshift as being cosmological, leading to the astounding properties of the objects as we described above. The article for *Nature* announcing the redshift in 3C 273 was published in March 1963, together with an article by Oke on the H-alpha line, and one by Greenstein and Matthews on 3C 48. They were preceded by an article by Hazard, Mackey, and Shimmins about the lunar occultations of 3C 273.

In retrospect, the question arises why the redshift of quasars was not noticed earlier. There was, of course, a mental barrier against considering the possibility of a star-like object having a redshift. This was because most stars in the sky belong to our Milky Way Galaxy, and have motions not much larger than 600 km/sec, corresponding to a redshift of 0.002. Even when I was in the process of taking wavelength ratios of the lines in 3C 273 and the Balmer series, I was only thinking of checking the regularity of the line spacings, even though the procedure is standard for deriving redshifts.

While identifying quasi-stellar radio sources on photographic plates, Sandage noticed in 1965 a number of stellar objects of similar properties that were not radio sources. These quasi-stellar objects had spectra and luminosities similar to the quasi-stellar radio sources. Both types of quasi-stellar sources soon became known as quasars, a name proposed by H.-Y. Chiu in 1964.

The nature of quasars remained uncertain until 1969, when Donald Lynden-Bell presented compelling arguments that they were massive black holes. Their enormous luminosities are caused by the accretion of gas and stars into the black hole. This fitted well with their high luminosities and their small sizes.

It was clear that with their high luminosities, quasars should be visible to enormous distances. I was able to derive a redshift of 2.0 for the quasar 3C 9 in 1965. It took the light from this object 10 billion years to reach Earth. Thus we observed the object as it was only 4 billion years after the big bang. The currently largest redshifts for quasars of more than 6 reach back to 1 billion years after the big bang. Clearly, the discovery of quasars opened up the exploration of the early stages of the Universe.