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The discovery of quasars

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Abstract. Although the extragalactic nature of quasars was discussed as early as 1960, it was rejected largely because of preconceived ideas about what appeared to be an unrealistically high radio and optical luminosity. Following the 1962 occultations of the strong radio source 3C 273 at Parkes, and the subsequent identification with an apparent stellar object, Maarten Schmidt recognized that the relatively simple hydrogen line Balmer series spectrum implied a redshift of 0.16. Successive radio and optical measurements quickly led to the identification of other quasars with increasingly large redshifts and the general, although for some decades not universal, acceptance of quasars as being by far the most distant and the most luminous objects in the Universe. Arguments for a more local population continued for at least several decades, fueled in part by a greater willingness to accept the unclear new physics needed to interpret the large observed redshifts rather than the extreme luminosities and energies implied by the cosmological interpretation of the redshifts.

Curiously, 3C 273, which is one of the strongest extragalactic sources in the sky, was first catalogued in 1959 and the magnitude 13 optical counterpart was observed at least as early as 1887. Since 1960, much fainter optical counterparts were being routinely identified using accurate radio interferometer positions, measured primarily at the Caltech Owens Valley Radio Observatory. However, 3C 273 eluded identification until the series of lunar occultation observations led by Cyril Hazard. Subsequent attempts to classify quasars into numerous sub-categories based on their observed optical, radio, IR and high energy properties have perhaps led to more confusion than clarity. However, quasars and the broader class of AGN are now a fundamental part of astrophysics and cosmology. They were the basis for the recognition of supermassive black holes in galactic nuclei, which are intimately tied to the formation and evolution of stars and galaxies.

Keywords : quasars: general – quasars: emission lines – radio continuum: stars – galaxies: distances and redshifts – galaxies: active – occultations – history and philosophy of astronomy

1. Historical background

The year 2013 marks the fiftieth anniversary of the discovery of quasars. It was on 5 February, 1963, that Maarten Schmidt at Caltech recognized that the spectrum of the magnitude 13 apparently stellar object identified with the radio source 3C 273 could be most straightforwardly interpreted by a redshift of 0.16. Subsequent work by Schmidt and others led to increasingly large measured redshifts and the recognition of the broad class of active galactic nuclei (AGN) of which quasars occupy the high luminosity end. Schmidt's discovery changed extragalactic astronomy in a fundamental way. Measured redshifts quickly went from about 0.5 to more than 2 in only a few years, making possible a new range of cosmological studies, as well as the realization that supermassive black holes which power radio galaxies and quasars play a prominent role in the evolution of galaxies. But the path to this understanding was a slow, tortuous one, with missed turns that could have earlier defined the nature of quasars.

The events leading up to the recognition of quasars as the extremely luminous nuclei of distant galaxies go back much earlier than 1963; indeed, one wonders why the extragalactic nature of quasars was not recognized well before 1963, and why 3C 273, which is the seventh brightest radio source in the northern sky away from the Galactic plane, was not identified at least one or two years earlier.

In the remainder of this section I review the early arguments and evidence for powerful activity in the nuclei of galaxies. In Section 2, I briefly review the status of extragalactic radio astronomy prior to the identification of 3C 48, and in Section 3, the identification of 3C 48, which might have been the first discovered quasar, but was unrecognized as such until the work on 3C 273 three years later as described in Section 4. In Section 5 I return to the issues surrounding 3C 48, and in Sections 6 and 7 the implications for cosmology and the arguments for non-cosmological interpretations of quasar redshifts. Sections 8 and 9 describe the discovery of radio quiet quasars and the proliferation of quasar categories and classifications. Finally, in Section 10, I summarize the history and remaining questions surrounding the discovery of quasars.

Probably the first person to note the enhanced activity in the nucleus of a galaxy was Edward Fath (1908) who reported on the nuclear emission line spectrum of NGC 1068. Later observations of strong nuclear emission lines by V. Slipher (1917), Edwin Hubble (1926), Milton Humason (1932), and Nick Mayall (1934, 1939) led Carl Seyfert (1943) to his now famous study of the enhanced activity in the nuclei of six galaxies (or as he called them, 'extragalactic nebulae'). Seyfert, as well as his predecessors, commented on the similarity with the emission line spectrum of planetary and other gaseous nebulae and that the lines are apparently Doppler broadened. There is no evidence that he ever continued this work, but nevertheless galaxies containing a stellar nucleus with strong broad emission (including forbidden) lines have become known as 'Seyfert Galaxies'. Unfortunately, Seyfert died in an automobile accident in 1960. Before his death, he served three years on the board of Associated Universities Inc. during the critical period when AUI was overseeing the early years of NRAO. It interesting to speculate whether if Seyfert had lived, his association with the radio astronomers at NRAO might have led to an earlier appreciation of the relationship between radio emission and nuclear activity.

However, it was Victor Ambartsumian who mainly championed the idea that something special was going on in the nuclei of galaxies. At the 1958 Solvey Conference, Ambartsumian (1958) proposed 'a radical change in the conception on the nuclei of galaxies', saying 'apparently we must reject the idea that the nuclei of galaxies is composed of stars alone'. He went on to conclude that, 'large masses of prestellar matter are present in nuclei'. Even earlier, Sir James Jeans (1929) wrote:

> 'The type of conjecture which presents itself, somewhat insistently, is that the centres of the nebulae are of the nature of "singular points", at which matter is poured into our universe from some other and entirely spatial dimension, so that to a denizen of our universe, they appear as points at which matter is being continually created.'

In a prescient paper, Hoyle and Fowler (1963) considered 'the existence at the very centre of galaxies of a stellar-type object of large mass . . . in which angular momentum is transferred from the central star to a surrounding disk of gas'.

2. Before quasars

When discrete sources of radio emission were discovered, they were first thought to be due to Galactic stars. Both, Karl Jansky and Grote Reber had shown that the diffuse radio emission was associated with the Milky Way, and since the Milky Way is composed of stars, it seemed natural that the discrete radio sources were likely connected with stars. Indeed for many years they were called 'radio stars'.

The first hint that at least some radio sources might be extragalactic came from a series of observations made by John Bolton, Gordon Stanley, and Bruce Slee (1949) using cliff interferometers in Australia and New Zealand. After months of painstaking observations, Bolton and his colleagues succeeded in measuring the positions of three strong radio sources with an accuracy better than half a degree. For the first time it was possible to associate radio sources with known optical objects. Taurus A, Centaurus A, and Virgo A were identified with the Crab Nebula, NGC 5128 and M87 respectively. NGC 5128, with its conspicuous dark lane, and M87, with its prominent jet, were well known to astronomers as peculiar galaxies. But, their 1949 paper, 'Positions of Three Discrete Sources of Galactic Radio Frequency Radiation', which was published in *Nature* mostly discussed the nature of the Crab Nebula. In a few paragraphs near the end of their paper, they commented, 'NGC 5128 and NGC 4486 (M87) have not been resolved into stars, so there is little direct evidence that they are true galaxies. If the identification of the radio sources are accepted, it would indicate that they are [within our own Galaxy]'. As implied by the title, Bolton, Stanley, and Slee dismissed the extragalactic nature of both Centaurus A and M87. When asked many years later why he didn't recognize that he had discovered the first radio galaxies, Bolton responded that he knew they were extragalactic, but that he also realized that the corresponding radio luminosity would be orders of magnitude greater than that of our Galaxy and that he was concerned that in view of this apparent extraordinary luminosity, a conservative *Nature* referee might hold up publication the paper. However, in a 1989 talk, Bolton (1990) commented that their 1949 paper marked the beginning of extragalactic radio astronomy. Nevertheless, for the next few years the nature of discrete radio sources remained controversial within the radio astronomy community, and many workers, particularly at the Cambridge University Cavendish Laboratory, continued to refer to radio stars.

Following the identification of Cygnus A with a magnitude 18 galaxy at $z = 0.06$, by Walter Baade and Rudolph Minkowski (1954), it became widely appreciated that the high latitude radio sources were in fact very powerful 'radio galaxies', and that the fainter radio sources might be at much larger redshifts, even beyond the limits of the most powerful optical telescopes such as the Palomar 200 inch. In a footnote to their paper, Baade and Minkowski confess that Cygnus A had been previously identified with the same galaxy by Mills and Thomas (1951) and by Dewhurst (1951), but at the time Minkowski was not willing to accept the identification with such a faint and distant nebula. Over the next five years, many other radio galaxies were recognized based on more accurate radio positions measured at Cambridge, and starting in 1960, with the Caltech interferometer, which John Bolton had built specifically to obtain more accurate radio source positions in order to enable more optical identifications. Recognizing that radio galaxies were characteristically the brightest galaxy in a cluster, it became clear to many that the search for distant galaxies needed to address the outstanding cosmological problems of the day should therefore concentrate on galaxies identified with radio sources. Moreover, it was naturally assumed that the smaller radio sources were most likely to be the more distant, so emphasis was given to the smallest radio sources, whose dimensions were determined with the long baseline radio linked interferometers at Jodrell Bank (Allen et al. 1960; Allen et al. 1962) and with the Caltech OVRO (Owens Valley Radio Observatory) interferometer.

Much of this work was carried out within a collaboration of scientists at Caltech and at the Mount Wilson and Palomar Observatories. John Bolton, Tom Matthews, Alan Moffet, Dick Read, and Per Maltby at the Caltech OVRO provided accurate radio positions, angular sizes, and optical identifications based on inspection of the 48 inch Schmidt prints and plates. At the Mt. Wilson and Palomar Observatories, Baade, Minkowski, and Allan Sandage teamed up with the Caltech radio astronomers to obtain 200 inch photographs and spectra. At Caltech, Jesse Greenstein, Guido Munch and, after Minkowski's retirement in 1960, Maarten Schmidt provided spectroscopic follow-up to determine the redshifts of radio galaxies.

This program had a dramatic success, when, using the 200 inch telescope during his last observing session before retiring, Minkowski (1960) determined a redshift of 0.46 of the 20.5 magnitude galaxy which was identified by Matthews and Bolton with 3C 295. This made 3C 295 by far the largest known redshift. Although previous to Minkowski's observation, the largest measured spectroscopic redshift was less than 0.2, curiously an unrelated foreground galaxy located only a few arcmin from 3C 295 was observed by Minkowski to have a redshift of 0.24, making it the second largest known redshift at the time. Yet, it would be another 15 years before a galaxy redshift greater than that of 3C 295 would be measured. Interestingly, 3C 295 was targeted not because of any special properties, but only because it was at a high declination, where an accurate declination could be measured with the OVRO interferometer, which at that time had only an East-West baseline.

3. 3C 48: The first radio star

By late 1960, it was widely accepted that radio sources located away from the Galactic plane were powerful distant radio galaxies (e.g., Bolton 1960). But, Bolton's Caltech colleague, Jesse Greenstein, a world expert on exotic stars, was said to have offered a bottle of the best Scotch whisky to whoever found the first true radio star. Meanwhile, in the quest to find more distant galaxies, the Caltech identification program concentrated on small diameter sources selected from the early OVRO interferometer observations and from unpublished long baseline interferometer observations at Jodrell Bank (Allen et al. 1962).

In 1960 Tom Matthews identified 3C 48 with what appeared to be a magnitude 16 star. Observations made by Allan Sandage using the two hundred inch telescope in September 1960 indicated a faint red wisp 3 arcsec by 8 arcsec in size. Spectroscopic observations by Sandage, Greenstein and Munch showed multiple emission and absorption lines as well as a strong UV excess, but attempts to identify the lines were inconclusive. On December 29, Sandage presented a late paper at the 107th meeting of the AAS in New York by Matthews, Bolton, Greenstein, Munch, and Sandage, which reflected the order of their involvement (Bolton 1990). But, by this time, Bolton had left Caltech to return to Australia to oversee the completion and operation of the Parkes 210 foot radio telescope. Unfortunately, abstracts of late AAS papers were not published at that time, and the only remaining written record of the talk is a news article on the *'First True Radio Star'* which appeared in the February 1961 issue of *Sky and Telescope*[1] and a report in the 1960–61 annual report of the Carnegie Institution of Washington.[2] Sky and Telescope cautiously reported that 'there is a remote possibility of that [3C48] may be a distant galaxy of stars; but there is general agreement among the astronomers concerned that it is a relatively nearby star with most peculiar properties'. Jesse Greenstein (1961) wrote an article in the Caltech Engineering and Science publication announcing, *'The First True Radio Star'*.

Subsequent study appeared to confirm the nature of 3C 48 as a true radio star, but with no proper motion as great as 0.05 arcsec/yr. Radio observations indicated angular dimensions less than 0.8 arcsec (Allen et al. 1962) and no measured radio variability (Matthews & Sandage 1963). Observations by Sandage at the 200 inch telescope showed that except for the faint 'wisp' most of the optical light was unresolved, that the color was 'peculiar' and that the optical counterpart varied by at least 0.4 mag over a time scale of months (Matthews & Sandage 1963). Greenstein (1962) made an exhaustive study of the optical spectrum. After two years of analysis, he submitted a paper to the *Astrophysical Journal* titled, 'The Radio Star 3C48', where he concluded that

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[1]Sky and Telescope, 1961, 21, 148. Curiously, there is no record of the 107th meeting of the AAS, at the American Institute of Physics Neils Bohr Library & Archives, although the records of the preceding and succeeding years still exist at AIP.

[2]Report of the Mount Wilson and Palomar Observatories in Carnegie Institution of Washington Yearbook, 60, 80.

3C 48 was the stellar remains of a supernova, and that the spectrum reflected highly ionized rare earth elements. The abstract states, 'The possibility that the lines might be greatly redshifted forbidden emissions in a very distant galaxy is explored with negative results', and the first sentence of the paper states, 'The first spectra of the 16th magnitude stellar radio source 3C48 obtained in October 1960 by Sandage were sufficient to show that this object was not an extragalactic nebula of moderate redshift'. Greenstein did discuss possible line identifications with several possible redshifts, and although he commented that except for 0.367 no redshift explains the strongest lines of any single ionization, he then maintained that, 'the case for a large redshift is definitely not proven'. Nevertheless, with great prescience, he then went on to point out that if the 3C 48 spectrum is really the redshifted emission spectrum of a galaxy, then for $\Delta\lambda/\lambda > 1$, Ly-$\alpha$ and other strong UV lines would be shifted into the visible spectrum. When asked years later why he rejected what appeared to be a very important and satisfactory interpretation in terms of a large redshift, Greenstein responded, 'I had a reputation for being a radical and was afraid to go out on a limb with such an extreme idea'.[3]

Matthews & Sandage (1963) succeeded in identifying two additional small diameter radio sources, 3C 196 and 3C 286, with 'starlike' optical counterparts. But the nature of these 'starlike' counterparts to compact radio sources remained elusive until the investigation of 3C 273 showed them to be distant unprecedentedly powerful objects.

4. 3C 273

3C 273, which is the seventh brightest source in the 3C catalogue, with a flux density comparable to that of 3C 295, was naturally included in the Caltech program to measure accurate positions with the goal of finding optical counterparts for several hundred sources from the 3C catalogue. By early 1961, the OVRO interferometer included both east–west and north–south baselines; so it was producing accurate positions for hundreds of radio sources (e.g., Greenstein 1961). Typical position accuracy was better than 10 arcsec for the stronger sources. Right ascensions were measured by Tom Matthews and others. The declination measurements were part of Richard Read's 1962 Caltech PhD thesis and were published in the July 1963 issue of the *Astrophysical Journal* (Read 1963). The right ascensions were not published until later (Fomalont et al. 1964), but the positions of many sources including 3C 273 were available to Caltech astronomers by 1961. Based on his measured declinations and right ascensions measured by other Caltech radio astronomers, Read (1962, 1963) discussed likely identifications of four sources, including 3C 273, with faint galaxies seen only in 200 inch plates. Read's declination differed by only one arcsecond from the currently accepted position of the quasar. An unpublished contemporaneous right ascension measured by the Caltech radio astronomers was within 2 arcseconds of the correct position.[4] But, the faint galaxy mentioned by Read, which Maarten Schmidt attempted to observe in May, 1962, was inexplicitly about an arcminute west of the correct position.

[3] Jesse Greenstein, private communication to K. Kellermann, January 1995.
[4] Papers of K. I. Kellermann, NRAO Archives.

The breakthrough occurred in 1962 with a series of lunar occultations of the radio source 3C 273 which were predicted to be observable with the 210-ft radio telescope at Parkes, NSW. Earlier, Cyril Hazard (1961, 1962), had used the Jodrell Bank 250-ft radio telescope to observe a lunar occultation of the radio source 3C 212. Hazard was able to determine the position of 3C 212 with an accuracy of 3 arcseconds but his inspection of Palomar Sky Survey plates failed to recognize the 19 magnitude stellar identification which later turned out to be a quasar. Although unresolved by the OVRO interferometer (Moffet 1962), 3C 273 was known from interferometer measurements at Jodrell Bank (Allen et al. 1962) and Nancay (Lequeux 1962) to be resolved on longer baselines so it was not on Matthews list of high priority small sources that might lead to an identification of a more distant galaxy than 3C 295. A full occultation of 3C 273 including immersion as well as emersion was predicted to occur on August 5, 1962 and was observed at Parkes at both 136 and 400 MHz. According to Hazard (1977, 1985) and Bolton (1990), Rudolph Minkowski had a Polaroid copy of a 48 inch Schmidt plate which indicated the incorrect faint galaxy identification which Schmidt had tried to observe in May of that year. According to Bolton (1990) earlier position measurements made with the Parkes telescope had established a tentative identification in between a mag 13 stellar object and an elongated feature seen on Minkowski's image. But according to Bolton, the position accuracy was not sufficient to determine whether the radio source was associated with the 'star' or with the elongated feature that looked like an edge-on galaxy, so there was great interest in the occultation to resolve the uncertainty. For the first occultation on May 15[5] only the immersion was visible, but although the observation was apparently not well planned, it did show diffraction fringes characteristic of a very small source; but was not adequate to derive a position. The 5 August event was more promising as both immersion and emission were visible; but there was a catch. Emersion of the radio source from behind the Moon was predicted to occur uncomfortably close to the 60 degree zenith angle limit of the Parkes telescope. To make sure that the event would not be missed due to an inaccurate position, as had some earlier predicted occultations, Bolton removed a ladder from the telescope structure and ground down part of the telescope gear box in order to extend the length of time the telescope could track. However, as it turned out, the occultation took place at precisely the predicted time, and so the rather drastic alteration of the telescope proved unnecessary. But, it made a good story which Bolton enjoyed telling and retelling.

From analysis of the diffraction pattern at 136 and 410 MHz obtained from the immersion and emersion of the source from behind the Moon, Hazard (1963) showed that 3C 273 was a complex source consisting of a small flat spectrum component (B) and an elongated steep spectrum component (A). Even before the occultation, at least Hazard,[6] was aware of the observations by James Lequeux (1962) using the Nancay interferometer in France to show that 3C 273 was double with an E–W separation of 14 arcsec, precisely the same value determined from the occultation. On August 20, just two weeks after the occultation, John Bolton wrote to Maarten Schmidt at Caltech discussing the Parkes program of radio source identifications and requesting optical follow-up from Palomar on a radio source located at −28 degrees declination. Somewhat parenthetically, or as an afterthought, he gave the occultation positions of 3C 273 components

[5]The date is erroneously given as April 15 in the Hazard et al. paper in Nature.

[6]Cyril Hazard interview with W. T. Sullivan III, 20 March 1973, NRAO Archives.

A and B, requesting that he pass them along to Tom Matthews, but he made no mention of the obvious optical counterparts in his letter.[7] In January 1963, Hazard wrote to Schmidt, 'I have heard . . . that you have succeeded in identifying the radio source 3C 273',[8] so it appears likely that even five months after the occultation neither Hazard nor anyone in Australia were fully convinced of association with the bright star that was known to be close to the position of 3C 273. It was probably Tom Matthews (Schmidt 1963) who provided the precise optical coordinates which showed that the magnitude 13 stellar counterpart was coincident with the radio component B and the fainter jet coincident with component A.

Unfortunately, 3C 273 was too close to the Sun to attempt any spectroscopy until December 1962, when Schmidt used the Palomar 200 inch to observe the spectrum. Based on the faint optical counterparts that were being associated with other radio sources, Schmidt (1983, 2011) has explained that he assumed that correct optical counterpart was the faint jet. Although at the time there were already three radio sources, 3C 48, 3C 196, and 3C 286 which had been identified with stellar counterparts, Schmidt (1983, 2011) assumed that the magnitude 13 stellar object was far too bright to be associated with the radio sources. Nevertheless, in order to eliminate the stellar object from further consideration, Schmidt decided to first obtain a spectrum of the 'star'. Having spent most of his 200 inch time observing very faint objects, Schmidt overexposed the spectrum on the first night. Although he obtained a properly exposed spectrum on 29 December, it wasn't until 6 February, 1963 that he recognized the simple Balmer series bands of Hβ, Hγ, Hδ, and Hϵ with a redshift of 0.158 and a corresponding optical luminosity some hundred times brighter than the typical galaxies previously identified with radio sources. Applying that redshift led Schmidt (1963) to recognize the observed band at 3239 Å to be Mg II with a rest wavelength of 2798 Å and another line at a rest wavelength of 5007 Å to be [O III] (Schmidt 1983). A low resolution infra-red observation by Oke (1963) showed the Hα line shifted to 7599 Å confirming Schmidt's redshift determination.

Re-inspection of the 3C 48 spectrum by Schmidt and Greenstein identified the broad line at 3832 Å to be Mg II redshifted by 0.3679 and the other 3C 48 lines fell into place as [Ne V], [O II], and [Ne III]. Greenstein recalled that Matthews had earlier suggested 'the possibility of a 37% redshift', so the 3C 48 paper was published by Greenstein and Matthews (1963), but no mention was made of any involvement by John Bolton.[9] The high luminosity implied by the observed redshifts along with the small size implied by Sandage's observation of variability was quite remarkable, and not immediately universally accepted.

The four, now classic, papers by Hazard et al. (1963), Schmidt (1963), Oke (1963), and Greenstein and Matthews (1963) were published as consecutive papers in the March 16, 1963 issue of Nature. Whether by error or intentionally, Hazard's name appeared in *Nature* with a CSIRO Radiophysics Laboratory affiliation, although Hazard was affiliated with the University

[7]Letter from John Bolton to Maarten Schmidt, August 20, 1962, Papers of K. I. Kellermann, NRAO Archives.

[8]Letter from Cyril Hazard to Maarten Schmidt, 31 January, 1963, Papers of K. I. Kellermann, NRAO Archives.

[9]Letter from JLG to KIK, March 30, 1966 claimed that Bolton played no role in the 3C 48 story. Papers of K. I. Kellermann, NRAO Archives. But see Section 5 below.

of Sydney. Relations between the University of Sydney and the Radiophysics Laboratory were at the time already strained, and this incident further exacerbated the existing tensions. Hazard had been invited by John Bolton, Taffy Bowen, and Joe Pawsey to use the Parkes telescope to observe the upcoming occultation. As a non-staff member, Hazard was not familiar with the operation of the telescope or the receivers, and so following standard practice for non Radiophysics observers, John Shimmins and Brian Mackey were added to the observing team to provide telescope and receiver support respectively (Bolton 1990). Haynes & Haynes (1993) attribute the error to an unintentional mistake on the part of the journal due to the change from a letter format as submitted to an article format as published.

5. 3C48 revisited

In 1989, John Bolton (1990) gave a talk to the Astronomical Society of Australia in which he reminisced about his work at Caltech during the period from 1955 to 1960 during which he was away from Australia to start the radio astronomy program at Caltech. In his talk, Bolton recalled that back in 1960, a full two years before the redshifts of 3C 273 and 3C 48 were announced, he had discussed a possible 3C 48 redshift of 0.37. Bolton (1990) wrote, ‘The best fit I could find for the one broad line and one narrow line which Jesse [Greenstein] had measured were with Mg II λ2798 and [Ne V] λ3426, and a redshift of 0.37’. Since a quarter of a century had passed before his 1989 talk, Bolton’s assertion was naturally viewed with skepticism and emphatically was rejected by Greenstein as a fabrication.[9] However, Bolton’s claim is supported by a handwritten letter from Bolton to Joe Pawsey dated 16 November, 1960, just one month before Bolton left Caltech for Australia to take charge of Parkes radio telescope, then under construction. Bolton wrote:[10]

> ‘I thought we had a star. It is not a star. Measurements on a high dispersion spectrum suggest the lines are those of Neon [V], Argon [III], and [IV] and that the redshift is 0.367. The absolute photographic magnitude is −24 which is two orders of magnitude greater than anything known . . . I don’t know how rare these things are going to be, but one thing is quite clear – we can’t afford to dismiss a position in the future because there is nothing but stars.’

But, just a month later, on December 19, Bolton wrote to Pawsey from the SS Orcades,[11] ‘The latest news on 3C 48 as I left Caltech was – It is most likely a star’. Bolton’s letter was mailed from Honolulu where the ship stopped on the way to Australia. Apparently, between November 16 and the time he sailed for Australia, Bolton had discussed 3C 48 with Ira Bowen, then director of the Mt. Wilson and Palomar Observatories and an expert on spectroscopy. Bowen and Greenstein had inexplicably argued that the dispersion of only a few angstroms in the calculated rest wavelengths of different lines was too great to accept the large redshift and the corresponding

[10] 16 November 1960 letter to Joe Pawsey, National Archives of Australia, C3830 Z3/1/X
[11] December 19, 1960 letter to Joe Pawsey, National Archives of Australia, C3830 Z3/1/X

extraordinary absolute magnitude of −24. Indeed, in a paper submitted on December 8, 1962, several months before Schmidt's 3C 273 break-through, Matthews and Sandage (1963) had written that they were not able to find 'any plausible combination of red-shifted emission lines'. Apparently Matthews had forgotten that earlier he had suggested to Greenstein that 3C 48 might have a 37% redshift. The paper was published in July, 1963, with a section discussing *'3C 48 as a Galaxy'* added after its redshift had been determined by Greenstein and Schmidt.

6. Quasars and cosmology

The discovery of quasars with their large redshifts and corresponding unprecedented large radio and optical luminosity generated a wide range of observational and theoretical investigations as well as a plethora of conferences, particularly the series of Texas Symposia on Relativistic Astrophysics and Cosmology (e.g., Robinson, Schild & Shucking 1964). Motivated by the possibility of extending the Hubble relation to higher redshifts and determining the value of the deceleration constant, q_o, for years there was an intense competition to find the highest redshifts. Within two years of the 3C 273 breakthrough, redshifts as high as 2 were reported by Schmidt (1965) and others; but redshifts greater than 3 were not observed until 1973 (Carswell & Strittmatter 1973).

Nevertheless, the discovery of quasars and more generally, Active Galactic Nuclei (AGN), has revolutionized extragalactic astronomy. In his classic paper written only five years after he determined the redshift of 3C 273, Schmidt (1968) used a sample of forty quasi-stellar radio sources to derive their luminosity function and to show that the space density dramatically evolves with cosmic time much in the same manner as powerful radio galaxies. A few years later, Schmidt (1970) extended the study to include optically selected, e.g., radio quiet quasars. Now fifty years later, quasar and AGN research have become part of mainstream astronomy with numerous AGN and quasar conferences held each year along with many books and probably thousands of papers having been published. Supermassive black holes first introduced to power quasars (Lynden-Bell 1969) are now thought to play a major role in galaxy formation and evolution.

7. Non-cosmological redshifts

In view of the apparent extraordinary properties of quasars, a number of well-respected astronomers argued that the large observed quasar redshifts were intrinsic and not due to Doppler shifts reflecting the expansion of the Universe. The possibility that the observed shifts might be gravitational redshifts was considered very early, but Schmidt & Greenstein (1964), showed that an interpretation in terms of gravitational redshifts was unrealistic.

Nevertheless, there were a number of observations which appeared to challenge the cosmological interpretation of the large observed redshifts (e.g., Hoyle & Burbidge 1966). These included:

- *The absence of any redshift-magnitude (Hubble) relation for either the radio or optical data* now understood as a result of the wide dispersion in quasar luminosity.
- *QSO clustering near galaxies:* For many years, Fred Hoyle, Geoffrey Burbidge, Halton (Chip) Arp, and others maintained that the density of quasars in the vicinity of galaxies significantly exceeds that found in random fields. Thus they argued that quasars are ejected from galaxies, but it was difficult to understand the absence of blue shifts in such a model. One, not very convincing explanation was that light is emitted only in the opposite direction from the motion in the manner of an exhaust, hence only redshifts are observed. In a variation on this interpretation, James Terrell (1965) suggested that quasars are ejected from the center of our Galaxy and have all passed the Earth, hence we only see redshifts from the receding objects.
- *Distribution of observed redshifts:* Analysis of the distribution of observed quasar redshifts suggested that there were preferred values with peaks near 1.955 (Burbidge & Burbidge 1967) and at multiples of 0.061 (Burbidge 1968).
- *Radio variability:* The discovery of radio variability and especially rapid intra-day variability in some quasars suggested such correspondingly small linear dimensions that if the quasars are at cosmological redshifts, the brightness temperature would exceed the inverse Compton limit of 10^{13} K (Hoyle et al. 1966, Kellermann & Pauliny-Toth 1969). This issue was addressed with the discovery of superluminal motion which is most straightforwardly understood as the effect of relativistic beaming which can easily diminish the intrinsic brightness temperature below the inverse Compton limit.
- *Superluminal motion:* Although relativistic beaming satisfactorily addresses the inverse Compton problem, it was still argued that the observed large angular speeds could be more easily understood if quasar redshifts are not cosmological, and the corresponding speeds subluminal. Indeed, Hoyle, Burbidge and others argued that the relativistic beaming interpretation still requires linear speeds unrealistically close to the speed of light. Still today, the physics of the process by which highly relativistic motions are attained and maintained remains elusive.

The arguments for non-cosmological redshifts lasted for several decades; many conferences were held and books written to debate the issues. The apparent anomalies were argued to be the result of a-posteriori statistics and in the case of redshift distributions, selection effects due to the limited number of strong quasar emission lines that could be observed combined with the narrow range of the observable optical window, and the blocking of spectral regions by night-sky lines. The arguments for non-cosmological redshifts only died when the proponents died or at least retired, but from time to time, they still surface (e.g., Lopez-Corredoira 2011).

8. Interlopers, blue stellar objects, and quasi stellar galaxies

Soon after the discovery of quasars, it was realized that the optical counterparts were unusually blue. This suggested that quasars might be identified by their blue color only, without the need for very precise radio positions. In pursuing radio source identifications with blue stellar objects (BSOs), Sandage (1965) noticed many BSOs not coincident with known radio sources, which he called 'interlopers' or 'quasi-stellar galaxies' or 'QSGs'. In a paper received at the *Astrophysical Journal* on May 15, 1965, Sandage estimated that the density of interlopers or QSGs was about 1000 times greater than 3C radio sources. The *Astrophysical Journal* editor was apparently so impressed that he rushed the paper into publication in the May 15 issue of the Journal. Sandage's paper was received with skepticism, no doubt in part generated by what was perceived as privileged treatment of his paper.

Fritz Zwicky (1965) immediately pointed out that

> 'All of the five quasi-stellar galaxies described individually by Sandage (1965) evidently belong to the subclass of compact galaxies with pure emission spectra previously discovered and described by the present writer.'

A few years later, he was less circumspect and wrote (Zwicky 1971)

> 'In spite of all these facts being known to him in 1964, Sandage attempted one of the most astounding feats of plagiarism by announcing the existence of a major new component of the Universe: the quasi-stellar galaxies ... Sandage's earthshaking discovery consisted in nothing more than renaming compact galaxies, calling them "interlopers" and quasistellar galaxies, thus playing the interloper himself.'

Zwicky (1963), in fact did report at the April 1963 meeting of the AAS that the 'radio stars' are thought to lie at the most luminous end of the sequence of compact galaxies. However, his paper on the same subject was rejected by the Astrophysical Journal editor, Chandrasekhar, who wrote that (Zwicky 1971), 'Communications of this character are outside the scope of this journal'.

Tom Kinman (1965), working at Lick, and Roger Lynds and C. Villere (1965) working at Kitt Peak, each concluded that most of Sandage's BSOs were just that, blue stellar objects, located in the Galaxy and not compact galaxies. But, we still recognize that there is a population of so called 'radio quiet' quasars, which are about an order of magnitude more numerous and three to four orders of magnitude less luminous than radio loud quasars.

9. Nomenclature

For the lack of any other name Schmidt & Matthews (1964) adopted the term *'quasi stellar radio sources'*. This was quite a mouthful, and in a Physics Today review article, Hong-Yee Chiu (1964) coined the term 'quasar' which became widely used in oral discussion and in the popular media, but was not accepted by the *Astrophysical Journal*. However, in his 1970 paper on the *'Space Distribution and Luminosity Function of Quasars'*, Schmidt (1970) wrote,

> 'We use the term "quasar" for the class of objects of starlike appearance (or those containing a dominant starlike component) that exhibit redshifts much larger than those of ordinary stars in the Galaxy. QSOs are quasars selected on the basis of purely optical criteria, while QSSs are quasars selected on both the optical and radio criteria'.

The ApJ editor, Chandrasekhar responded with a footnote saying:

> 'The Astrophysical journal has until now not recognized the term "quasar"; and it regrets that it must now concede: Dr. Schmidt feels that, with his precise definition, the term can no longer be ignored.'

The term 'quasar' has caught on and is now commonly used in both the popular and professional literature. However, as observations have been extended to cover the entire electromagnetic spectrum, and as improvements in technology have resulted in increasingly detailed descriptions of both continuum and line spectra, variability, and morphology; quasars have become classified and sub-classified based on their line spectra, as well as their radio, optical, and high energy spectral distribution. Optical spectroscopy and photometry has defined QSO1s, QSO2s, BALs, Liners, and BL Lacs, collectively referred to as QSOs. Radio astronomers have defined Flat Spectrum and Steep Spectrum Radio Quasars, Radio Loud and Radio Quiet Quasars. Radio quiet quasars have been referred to as Interlopers, QSGs, and BSOs. Relativistically beamed quasars are known as blazars; X-ray and gamma-ray observations have defined High and Low Spectral Peaked Quasars. Collectively they are all known as Active Galactic Nuclei (AGN), although the term AGN was originally defined to cover the low luminosity counterpart to powerful quasars.

Further background on the early controversies surrounding the discovery of radio galaxies and their implications for cosmology can be found in the excellent books by Edge and Mulkay (1976) and Sullivan (2009). Shields (1999) and Collin (2006) have given accounts of the history of quasars and AGN, in particular the subsequent extensive development of the field over the past half century.

10. Summary, uncertainties, and speculations

Quasars and AGN are now a fundamental part of astrophysics and cosmology. The understanding that they are powered by accretion onto a supermassive black hole has had a profound impact on theories of galaxy formation and evolution as well as motivating extensive investigations of black hole physics.

Although both radio and optical astronomers were concentrating on small diameter radio sources in their quest to locate high redshift galaxies, the break-through occulation observations of 3C 273 in 1962 were unrelated to the quest for distant galaxies. Indeed, the known relatively large size of the 3C 273 radio source apparently discouraged further investigation until the 1962 series of occultations. Fifty years later, it remains unclear who first recognized that the magnitude 13 'stellar' object was indeed the optical counterpart of 3C 273 and not a foreground star. In a February, 1963 letter to Sir Bernard Lovell (1974), Hazard commented that 'We noticed this star some months ago on a 200″ plate'. Bolton (1990) later claimed that the goal of the occultation was to determine whether the radio source was associated with the 'star' or nebulosity, but if he knew the radio position that well, why did he needlessly cut up the gear box and remove the ladder, and when writing to Schmidt in August 1962 about the occultation, why did he only communicate the radio positions, and uncharacteristically make no mention of the obvious optical counterparts. Indeed, he asked Schmidt to 'pass on to Tom the following positions'. In his classic paper reporting the redshift, Schmidt (1963) thanked Tom Matthews for drawing his attention to the magnitude 13 'star', although in a 2012 interview with the author, Matthews denied any involvement in the 3C 273 saga.

It remains unclear why the strong radio source 3C 273 was not identified earlier with its mag 13 counterpart. Clearly Caltech was measuring accurate radio source positions as much as two years earlier and had the resources to identify 3C 273 as early as 1961. Although the possibility of identification with apparent stellar objects was already well established with the identifications of the faint optical counterparts 3C 48, 3C 196, and 3C 286, the association with a magnitude 13 stellar object apparently appeared too extreme to seriously consider. The 19.5 magnitude galaxy first thought to be the optical counterpart of 3C 273 was observed by Schmidt in May 1962, although it was about a minute of arc west of the true position. Schmidt and the Caltech radio astronomers must have believed that the position error was not more than a few arc seconds, as that kind of accuracy would be required for identification with a 19th or 20th magnitude galaxy. An accurate radio position was known among the Caltech radio astronomers perhaps as early as 1961, and certainly prior to Schmidt's May 1962 200 inch observations. It seems that somewhere along the line, there may have been error in conveying the OVRO radio position to the optical astronomers.

Sooner or later; probably sooner, 3C 273 would have been identified on the basis of an accurate interferometer position, and should have been at least a year or two earlier. Interestingly, it was possible to recognize the 'large' redshift of 3C 273, not because it was large, but because it was so 'small' that the Balmer series was still seen within the small classical optical window. 3C 273 is probably unique in being the only quasar whose spectrum can be so easily determined without prior knowledge of the line identification.

Two years earlier the possibility that 3C 48 was a distant galaxy had been discussed at least by Bolton, Greenstein, Matthews and Bowen, but was apparently rejected in part because of a very small discrepancy in the calculated line rest wavelengths, or perhaps more important because they were unwilling to accept the implied huge luminosity, just as Bolton, Stanley, and Slee rejected the extragalactic nature of radio galaxies in 1949 because they did not believe the high apparent radio luminosity. It may be relevant that while others were looking for distant galaxies, Bolton may have wanted to believe that he had discovered the first radio star. So 3C 48 played no direct role in the discovery of quasar redshifts. Prior to Schmidt's February 1963 realization of the 3C 273 redshift, Greenstein as well as Matthews and Sandage had submitted separate papers to the ApJ interpreting the 3C 48 spectrum as a Galactic star. After Schmidt's discovery, Greenstein withdrew his paper, while Matthews & Sandage (1963) added a section based on the 0.37 redshift reported by Greenstein & Matthews (1963).

The subsequent search for ever larger redshifts following the 1963 understanding of the 3C 48 and 3C 273 spectra was highly competitive, not only among the large optical observatories, but it also contributed to the increasing tensions between Caltech and Carnegie astronomers in Pasadena (Waluska 2007). The current largest known quasar redshift belongs to ULAS J1120+064 with a redshift of 7.1 (Mortlock et al. 2011). However, it is now gamma-ray bursts and ULIRGS, not quasars that are the most distant and the most luminous objects in the Universe, and gravitational lensing has enabled the detection of a starburst galaxy with a probable redshift of close to 10 (Zheng et al. 2012) well in excess of any known quasar.

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