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Quasars

To the naked eye the night sky is filled with stars. But outside of a quite narrow slice of the whole electromagnetic spectrum a radically different sky is seen. Over two huge frequency ranges, each about 10 decades broad, utterly different objects dominate the view. Both at the long, radio wavelengths, and at the high X-ray and γ-ray energies, the brightest things in the sky are *quasars*. Only in the three decades of frequency from the ultraviolet, through the visible band and into the infrared do stars dominate, and in the infrared much of the starlight is seen only indirectly, having been absorbed and re-emitted by dust around the stars. Three decades is much broader than the octave-wide band to which our human eyes are sensitive but, compared with the 20 decades of frequency opened up to astronomy during the space age, it is small.

Quasars[1] are truly space-age astrophysics. Of the two wide bands where quasars dominate, the radio sky can be explored quite well from the ground. To explore the high-energy sky though we have no choice but to use telescopes mounted on spacecraft.

What are these objects that dominate the sky over most of the spectrum? In complete contrast to stars, quasars are extremely distant objects seen back to early cosmic times, and are the most powerful ("luminous") continuous[2] sources of radiation in the Universe. Moreover, the light emitted by quasars, even though it reaches to the highest energy γ-rays we can measure, is not the whole of the quasar power output. They also shoot out enormous jets of fast particles, travelling at 99.999% of the speed of light. These jets stay narrow over huge distances, easily as large as the distances between whole galaxies. Such unusual objects as quasars should surely be found in unusual places, and indeed quasars inhabit the very centers ("nuclei") of galaxies. We believe that the origin of the strange properties of quasars is a black hole with a huge mass, 10^6 to 10^9 times that of the Sun.

Here I give a personal view of quasars across these 20 decades of spectrum, and across four decades of discovery, of which I have only witnessed two myself. After telling the history of quasar discovery, I set out seven key quasar mysteries, describe how space obsevations gradually brought the whole quasar phenomenon into view, and then explain each mystery, so far as we now can. I end with a few speculations on where quasar research will go next.

1 A QUICK QUASAR HISTORY

Understanding the quasar puzzle has been a long-term program. There were hints of strange activity in the nuclei of some galaxies as long ago as 1917 when Slipher found extraordinarily broad emission lines coming from the center of the galaxy NGC 1068, and the next year when Curtis found a jet pointing straight out of the center of the elliptical galaxy M87 in Virgo. Quasar prehistory took another step, 25 years later, when Karl Seyfert's 1943 PhD thesis described a few galaxies with extremely rapid gas motions in their nuclei (as determined from the Doppler-shifted width of their peculiar spectral emission lines; Slipher had rejected this explanation). Just a few years later, using surplus World War II radar equipment, radio astronomy blossomed, and for the first time found a sky not dominated by stars. In 1953 some of these new radio sources turned out to

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[1] For simplicity and clarity I will refer to all the types of non-stellar "activity" in galactic nuclei as "quasars," even though the research literature carefully distinguishes high-luminosity "quasars" from lower luminosity "active galactic nuclei" (or AGNs). Evidence for any basic physical difference between these types of active objects has diminished, essentially to the vanishing point.

[2] For a few seconds or minutes a gamma-ray burst can outshine any quasar.

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come in pairs, either side of a galaxy, suggesting ejection from the galaxy, but there was little hard evidence for this.

The true history of quasars did not begin for another decade, until 1963. Hard-won precise positions of radio sources enabled the large optical telescopes of the day to take spectra of whatever optical object lay at that position. Some showed the starlight of normal galaxies, but often at large distances (as measured by the redshifts of their spectral lines, using the Hubble relation between redshift and distance that describes the expansion of the Universe) (Chapter 17). The spectra of those with compact, "stellar"-looking, optical objects, though, had a baffling series of strong, broad emission lines. It took three years before Maarten Schmidt realized that one of these "radio stars" was actually at a large redshift, and so – given the Hubble relation between redshift and distance – presumably lay at a large distance from us. This in turn implied a prodigous luminosity.

Schmidt (1990) relates how his key discovery was made:

> The puzzle was suddenly resolved in the afternoon of February 5, 1963, while I was writing a brief article about the optical spectrum of 3C 273. Cyril Hazard had written up the occultation results for publication in *Nature* and suggested that the optical observations be published in an adjacent article. While writing the manuscript, I took another look at the spectra. I noticed that four of the six lines in the photographic spectra showed a pattern of decreasing strength and decreasing spacing from red to blue. For some reason, I decided to construct an energy-level diagram based on these lines.
>
> I must have made an error in the process which seemed to contradict the regular spacing pattern. Slightly irritated by that, I decided to check the regular spacing of the lines by taking the ratio of their wavelengths to that of the nearest line of the Balmer series. The first ratio, that of the 5630 line to H-beta, was 1.16. The second ratio was also 1.16. When the third ratio was 1.16 again, it was clear that I was looking at a Balmer spectrum redshifted by 0.16.
>
> I was stunned by this development: stars of magnitude 13 are not supposed to show large redshift! When I saw Jesse Greenstein minutes later in the hallway and told him what had happened, he produced a list of wavelengths of emission lines from a just completed manuscript about the spectrum of 3C 48. Being prepared to look for large redshift, it took us only minutes to derive a redshift of 0.37.
>
> The interpretation of such large redshifts was an extraordinary challenge. Greenstein and I soon found that an explanation in terms of gravitational redshift was essentially impossible on the basis of spectroscopic arguments. We recognized that the alternative explanation in terms of cosmological redshifts, large distances, and enormous luminosities and energies was very speculative but could find no strong arguments against it. The results for 3C 273 and 3C 48 were published six weeks later in four consecutive articles in *Nature* (Hazard, Mackay, and Shimmins 1963; Schmidt 1963; Oke 1963; Greenstein and Matthews 1963).

So these things were not stars, they simply appeared stellar on photographs, and hence they were dubbed "quasi-stellar objects" which quickly became "quasars" (Hazard 1979). Astronomers were not prompt to accept the idea that quasars were at cosmological distances. This was not because this distance seemed too great: after all, there was already the example of the large redshift (z = 0.46) of the radio galaxy 3C 295. The problem was that, if the redshifts implied distances according to the normal Hubble law (Chapter 17), then it implied *a second power source must be at work in the Universe, beyond the nuclear burning at the centers of stars*. That is because it is one thing is to find that a steady source is very distant and powerful, and quite another thing to find that a *variable* source is far away, because then it must emit its power from a region smaller than the time it takes light to cross it. In the case of quasars this means the power of a whole galaxy of stars comes from a region smaller than the Solar System! (r(Solar System) $\sim 50r$(Earth–Sun) = 50 AU = 7.5×10^{14} cm.) Any such source has to be more efficient than nuclear burning can be (see next section). And the first quasars found, 3C 273 and 3C 48, indeed varied quite strongly. It was this variability that had fixed the idea in astronomers' minds that these sources, of stellar optical appearance, must be nearby stars. But the high redshifts made that position untenable. In the 40 years since the first redshift of 0.16, quasars have continued to be found out to larger and larger redshifts (Figure 1), reaching 5.8 in 2000, implying they were already around when the Universe was only 5% of its current age, or less than 1 billion years old.

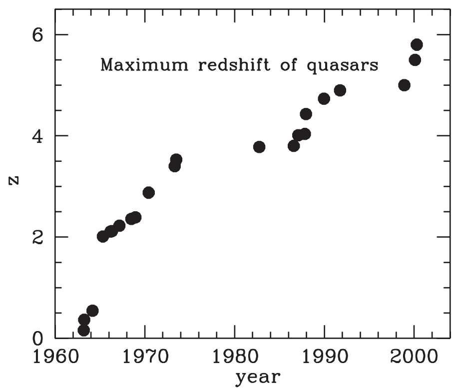

Figure 1 The largest redshift of quasars as a function of time. The current record is $z = 5.80$. (From Fan *et al.* 2001.) For early data see Schneider *et al.* (1992) and Fan *et al.* (1999).

2 SEVEN QUASAR MYSTERIES

The huge research literature on quasars revolves around a quite small number of central questions or mysteries. While these are capable of infinite subdivision I believe there are just seven basic mysteries.

It is remarkable that with the first quasar papers, already four of the seven quasar mysteries were laid out:

1. *Quasar luminosities are enormous, and arise from tiny regions*. The power from quasars covers a wide range ($>10^7$) from object to object: from $<10^{40}\,\mathrm{erg\,s^{-1}}$ to $>10^{47}\,\mathrm{erg\,s^{-1}}$, and can compete with, and easily exceed, that of a whole galaxy of 10^{11} stars ($\sim 10^{44}\,\mathrm{erg\,s^{-1}}$). When Mathews and Sandage (1963) found that quasars could vary their power output by 40% in just a few months, then it seemed that all this luminosity must come from a region similar in size to our Solar System. (From the simple "light travel time argument": a source cannot vary coherently in less time than a light signal takes to cross the source. So if a source varies in a day, it is no bigger than a light-day across (but beware of high velocities; Chapter 24).) Moreover the radio galaxies required that quasars put out enormous power over a long time period since the total energy stored in the giant radio lobes must be $>10^{60}$ ergs (Burbidge 1959). At this point it became a good bet that an energy source quite different from, and much more efficient than, nuclear burning in stars was at work.
2. *Quasar spectra are nothing like that of starlight*. Stars have more or less black-body spectra with well-defined temperatures of a few thousand degrees, so their emission in the radio band is tiny. Instead quasars can have huge radio luminosities with spectra that follow a simple straight-line form in log (flux) vs. log (frequency), i.e., a "power law" from $\sim$100 MHz to $\sim$100 GHz. So being bright in the radio does not simply mean that they are very cold objects. Their optical spectra have no obvious thermal peak either, but also have a power law shape from $\lambda = 1\,\mu\mathrm{m}$ to $0.1\,\mu\mathrm{m}$ (Figure 3). Confusingly at first this meant that quasars were both "bluer" than stars (i.e., had more short-wavelength emission than expected based on their visual brightness) and "redder" than stars (that is, the same at long wavelengths)! The whole spectrum is not just one power law though, since the radio and optical power laws do not join up. When X-ray spectra first became available, they too had a power-law shape, and again it did not connect with the optical or radio power laws (Figure 3). In this sense quasars have no temperature, and so were called "non-thermal" sources. That does not mean though that no combination of thermal processes underlies the production of the quasar continuum (see Section 5.2). This failure to drop off in power at either long or short wavelengths is the feature that makes quasars dominate the sky over most of the spectrum.
3. *Quasars accelerate material to high velocities*. The widths of the emission lines reach up to 10% of the speed of light ($0.1c$), although most are a smaller, but still considerable, $\sim 0.03c$. Some quasars show absorption lines, and some others show X-ray emission lines, implying velocities up to $0.2c$–$0.3c$. Most extreme of all, to create the observed "superluminal" motions in blazars requires $\delta \sim 10$, i.e., $\upsilon \sim 0.999c$ (Chapter 24; Ghisellini *et al*. 1993). Ways to produce the broad emission and absorption lines without using mass motions are contrived, but not impossible. Large velocities in astronomy imply deep gravitational wells (to accelerate matter, or to produce a general relativistic gravitational redshift), except for short-lived explosive events like supernovae.
4. *Quasars have linear symmetry*. As radio maps became more detailed through the exploitation of interferomety (work which led to a Nobel prize for two pioneers, Martin Ryle and Anthony Hewish) most of the radio sources were found to have a "double lobe" structure (Jennison and Das Gupta 1953) extending well beyond the galaxies they straddled. With the advent of the Very Large Array (VLA) in the 1970s these lobes could be mapped in detail at high dynamic range revealing pairs of large (10^{22}–10^{24} cm) highly structured bubbles (Figure 2). In many, but by no means all, cases the central galaxy had a nucleus with a spectrum like that of a quasar. Forty years later the fine detail of Hubble Space Telescope images showed that even the quasars that are not bright radio sources have a linear symmetry. Clear cone-shaped structures were seen stretching over a galaxy scale (10^{22} cm). In high-redshift radio-loud quasars (primarily in "radio galaxies") Hubble images showed galaxy-scale optical line emission aligned with the radio jets. A big clue to the inner structure of quasars has to lie in this symmetry.

From these four mysteries an outline of quasars was already becoming clear: a large mass in a small region suggested that the, then outlandish seeming, concept of a black hole might underlie quasar physics, while the symmetry suggested a spin axis, either of the black hole or of a rotating gas disk. A short paper by Donald Lynden-Bell (1969) put this together with extraordinary elegance. He pointed out that energy release from gravitational infall is more efficient than nuclear burning for any mass large enough to produce quasar luminosities. He then outlined how to release this energy as radiation: any material falling onto a black hole from some large distance will have some angular momentum around the black hole and so, unless the incoming matter is perfectly spherically symmetrical, the material will fall into a flattened shape to form an orbiting disk. (This is common in astronomy, recall Saturn's rings, or nascent planetary systems.) If

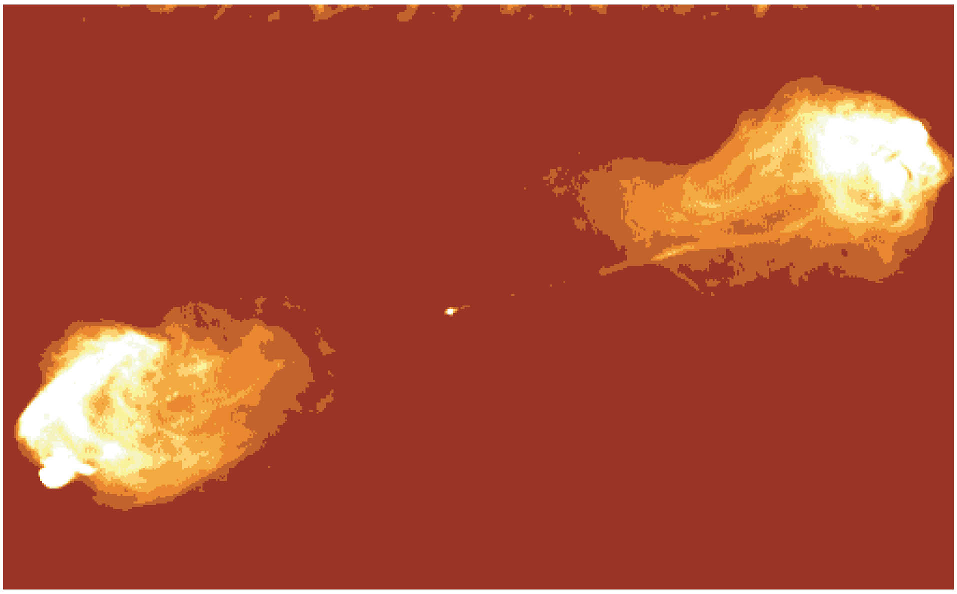

Figure 2 The complex two-sided radio structure of Cygnus A as imaged by the VLA. The large features, or "lobes", are fed by a jet of relativistic particles coming out of the central "core" (white dot), which lies at the nucleus of a large galaxy. (Perley *et al*. 1984; courtesy NRAO.)

enough matter accumulates then some (undertermined) form of viscous friction between adjacent orbits will drag on the faster moving material, moving angular momentum outward, and allowing matter to fall inward, eventuall accreting into the central black hole. As the matter falls inward the gravitational potential energy is released as radiation. At each radius the radiation will be more or less a black body, but since each radius emits a different temperature (getting hotter inward, as the potential gradient of the black hole steepens) so the summed emission from all radii looks nothing like a black body, in fact it can mimic a power law.

These "accretion disks" have since been found in our galaxy around many compact objects: white dwarfs, neutron stars, and stellar-mass black holes (Chapter 32), beginning with the discoveries of the Uhuru satellite (Giacconi and Gursky 1974). These smaller systems in which it was possible to establish that a black hole was almost certainly present made the idea of black holes and accretion disks more familiar and better understood, and they are now a conventional part of astrophysics (Frank *et al*. 1985, 1992). Nikolai Shakura and Rashid Sunyaev (1973) expanded on accretion disk theory by cleverly hiding all the unknown physics of viscosity in a parameter, α, and working out the disk behavior as a function of α.

It took only a few years of searching for fainter and fainter optical counterparts of radio sources up to higher and higher redshifts to discover two further mysteries:

5. *Radio-loud quasars are just the tip of the iceberg*. The blue "non-thermal" spectra of quasars made them easy to pick out from normal stars in large numbers just from a pair of photographs taken through different color filters. This "color selection" was used to find the quasar using the, initially quite uncertain, radio source positions. Hence quite a large area of sky was photographed for each radio source. Alan Sandage (1965) first saw that along with the radio-emitting blue quasar, there were many more blue "interlopers" that had nothing to do with the radio source. Spectra showed that these too were quasars, but ones which were "radio quiet." Radio-quiet quasars turn out to be 10 times more common than the original quasars, which are now called, with impeccable logic, "radio-loud quasars." The difference between radio-loud and radio-quiet quasars is found only in the radio spectrum (and possibly the γ-ray spectrum). The rest of the spectrum, from far-IR to hard X-rays is essentially the same (Elvis *et al*. 1994). (A slight difference of power-law slope in the X-rays being the only exception.) Yet the difference in the radio band is huge, a factor of ~ 100–10^4 in the ratio of radio to optical luminosity separates the two classes.
6. *Quasars are far less common now than they were in the distant past*. This was termed quasar "evolution".* The

*I find this an unfortunate choice. All we really mean is "change with time." In biology evolution demands mutation, reproduction, and selection, and is an active, unpredictable process that will produce different outcomes even with identical starting conditions. "Evolution" in astronomy is merely the playing out of physical processes, with no reproduction or competition and with a predictable outcome. Chaotic systems are an exception but still involve no analogs to the biological process of evolution.

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