Quasar

Quasar, an astronomical object of very high luminosity found in the centres of some galaxies and powered by gas spiraling at high velocity into an extremely large black hole. The brightest quasars can outshine all of the stars in the galaxies in which they reside, which makes them visible even at distances of billions of light-years. Quasars are among the most distant and luminous objects known.

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Six quasar host galaxies, as observed by the Hubble Space Telescope.Shown are apparently normal, solitary galaxies (left), colliding galaxies (centre), and merging galaxies (right).

Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC96-35a)

Discovery of quasars

The term *quasar* derives from how these objects were originally discovered in the earliest radio surveys of the sky in the 1950s. Away from the plane of the Milky Way Galaxy, most radio sources were identified with otherwise normal-looking galaxies. Some radio sources, however, coincided with objects that appeared to be unusually blue stars, although photographs of some of these objects showed them to be embedded in faint, fuzzy halos. Because of their almost starlike appearance, they were dubbed “quasi-stellar radio sources,” which by 1964 had been shortened to “quasar.”

Quasar 1229+204, as observed by the Hubble Space TelescopeThis picture shows that the quasar is surrounded by spiral arms characteristic of galaxies. The tremendous light generated by quasars and their great distance from Earth work to obscure the fainter galactic structures in which they are embedded. This quasar is apparently fueled by a collision between its host galaxy and a dwarf galaxy.

Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC94-16)

The optical spectra of the quasars presented a new mystery. Photographs taken of their spectra showed locations for emission lines at wavelengths that were at odds with all celestial sources then familiar to astronomers. The puzzle was solved by the Dutch American astronomer Maarten Schmidt, who in 1963 recognized that the pattern of emission lines in 3C 273, the brightest known quasar, could be understood as coming from hydrogen atoms that had a redshift (i.e., had their emission lines shifted toward longer, redder wavelengths by the expansion of the universe) of 0.158. In other words, the wavelength of each line was 1.158 times longer than the wavelength measured in the laboratory, where the source is at rest with respect to the observer. At a redshift of this magnitude, 3C 273 was placed by Hubble’s law at a distance of slightly more than two billion light-years. This was a large, though not unprecedented, distance (bright clusters of galaxies had been identified at similar distances), but 3C 273 is about 100 times more luminous than the brightest individual galaxies in those clusters, and nothing so bright had been seen so far away.

quasar

3C 273, the brightest quasar, photographed by the Hubble Space Telescope's Advanced Camera for Surveys. The black region at the centre of the image is blocking light from the central object, revealing the host galaxy of 3C 273.

NASA/STScI/ESA

An even bigger surprise was that continuing observations of quasars revealed that their brightness can vary significantly on timescales as short as a few days, meaning that the total size of the quasar cannot be more than a few light-days across. Since the quasar is so compact and so luminous, the radiation pressure inside the quasar must be huge; indeed, the only way a quasar can keep from blowing itself up with its own radiation is if it is very massive, at least a million solar masses if it is not to exceed the Eddington limit—the minimum mass at which the outward radiation pressure is balanced by the inward pull of gravity (named after English astronomer Arthur Eddington). Astronomers were faced with a conundrum: how could an object about the size of the solar system have a mass of about a million stars and outshine by 100 times a galaxy of a hundred billion stars?

The right answer—accretion by gravity onto supermassive black holes—was proposed shortly after Schmidt's discovery independently by Russian astronomers Yakov Zel'dovich and Igor Novikov and Austrian American astronomer Edwin Salpeter. The combination of high luminosities and small sizes was sufficiently unpalatable to some astronomers that alternative explanations were posited that did not require the quasars to be at the large distances implied by their redshifts. These alternative interpretations have been discredited, although a few adherents remain. For most astronomers, the redshift controversy was settled definitively in the early 1980s when American astronomer Todd Boroson and Canadian American astronomer John Beverly Oke showed that the fuzzy halos surrounding some quasars are actually starlight from the galaxy hosting the quasar and that these galaxies are at high redshifts.

By 1965 it was recognized that quasars are part of a much larger population of unusually blue sources and that most of these are much weaker radio sources too faint to have been detected in the early radio surveys. This larger population, sharing all quasar properties except extreme radio luminosity, became known as "quasi-stellar objects" or simply QSOs. Since the early 1980s most astronomers have regarded QSOs as the high-luminosity variety of an even larger population of "active galactic nuclei," or AGNs. (The lower-luminosity AGNs are known as "Seyfert galaxies," named after the American astronomer Carl K. Seyfert, who first identified them in 1943.)

Finding quasars

Although the first quasars known were discovered as radio sources, it was quickly realized that quasars could be found more efficiently by looking for objects bluer than normal stars. This can be done with relatively high efficiency by photographing large areas of the sky through two or three different-coloured filters. The photographs are then compared to locate the unusually blue objects, whose nature is verified through subsequent spectroscopy. This remains the primary technique for finding quasars, although it has evolved over the years with the replacement of film by electronic charge-coupled devices (CCDs), the extension of the surveys to longer wavelengths in the infrared, and the addition of multiple filters that, in various combinations, are effective at isolating quasars at different redshifts. Quasars have also been discovered through other techniques, including searches for starlike sources whose brightness varies irregularly and X-ray surveys from space; indeed, a high level of X-ray emission is regarded by astronomers as a sure indicator of an accreting black-hole system.

Physical structure of quasars

Quasars and other AGNs are apparently powered by gravitational accretion onto supermassive black holes, where "supermassive" means from roughly a million to a few billion times the mass of the Sun. Supermassive black holes reside at the centres of many large galaxies. In about 5–10 percent of these galaxies, gas tumbles into the deep gravitational well of the black hole and is heated to incandescence as the gas particles pick up speed and pile up in a rapidly rotating "accretion disk" close to the horizon of the black hole. There is a maximum rate set by the Eddington limit at which a black hole can accrete matter before the heating of the infalling gas results in so much outward pressure from radiation that the accretion stops. What distinguishes an "active" galactic nucleus from other galactic nuclei (the 90–95 percent of large galaxies that are currently not quasars) is that the black hole in an active nucleus accretes a few solar masses of matter per year, which, if it is accreting at around 1 percent or more of the Eddington rate, is sufficient to account for a typical quasar with a total luminosity of about 10^{39} watts. (The Sun's luminosity is about 4×10^{26} watts.)

Quasar and its companion galaxy colliding, as observed by the Hubble Space Telescope.The image on the left shows a quasar and (pointing lower right) one of its spiral arms. In the image on the right, the companion galaxy is visible as a bright spot just above the quasar.

Photo AURA/STScI/NASA/JPL (NASA photo # STScI-PRC96-35b)

In addition to black holes and accretion disks, quasars have other remarkable features. Just beyond the accretion disk are clouds of gas that move at high velocities around the inner structure, absorbing high-energy radiation from the accretion disk and reprocessing it into the broad emission lines of hydrogen and ions of other atoms that are the signatures of quasar spectra. Farther from the black hole but still largely in the accretion disk plane are dust-laden gas clouds that can obscure the quasar itself. Some quasars are also observed to have radio jets, which are highly collimated beams of plasma propelled out along the rotation axis of the accretion disk at speeds often approaching that of light. These jets emit beams of radiation that can be observed at X-ray and radio wavelengths (and less often at optical wavelengths).

Because of this complex structure, the appearance of a quasar depends on the orientation of the rotation axis of the accretion disk relative to the observer's line of sight. Depending on this angle, different quasar components—the accretion disk, emission-line clouds, jets—appear to be more or less prominent. This results in a wide variety of observed phenomena from what are, in reality, physically similar sources.

Evolution of quasars

The number density of quasars increases dramatically with redshift, which translates through Hubble's law to more quasars at larger distances. Because of the finite speed of light, when quasars are observed at great distances, they are observed as they were in the distant past. Thus, the increasing density of quasars with distance means that they were more common in the past than they are now. This trend increases until "look-back times" that correspond to around three billion years after the big bang, which occurred approximately 13.5 billion years ago. At earlier ages, the number density of quasars decreases sharply, corresponding to an era when the quasar population was still building up. The most distant, and thus earliest, quasars known were formed less than a billion years after the big bang.

The quasar PKS 2349−014 (bright central disk), several billion light-years from Earth. It appears to be merging with a companion galaxy.

John Bahcall, Institute for Advanced Study, NASA

Individual quasars appear as their central black holes begin to accrete gas at a high rate, possibly triggered by a merger with another galaxy, building up the mass of the central black hole. The current best estimate is that quasar activity is episodic, with individual episodes lasting around a million years and the total quasar lifetime lasting around 10 million years. At some point, quasar activity ceases completely, leaving behind the dormant massive black holes found in most massive galaxies. This "life cycle" appears to proceed most rapidly with the most-massive black holes, which become dormant earlier than less-massive black holes. Indeed, in the current universe the remaining AGN population is made up predominantly of lower-luminosity Seyfert galaxies with relatively small supermassive black holes.

In the present-day universe there is a close relationship between the mass of a black hole and the mass of its host galaxy. This is quite remarkable, since the central black hole accounts for only about 0.1 percent of the mass of the galaxy. It is believed that the intense radiation, mass outflows, and jets from the black hole during its active quasar phase are responsible. The radiation, outflows, and jets heat up and can even remove entirely the interstellar medium from the host galaxy. This loss of gas in the galaxy simultaneously shuts down star formation and chokes off the quasar’s fuel supply, thus freezing both the mass in stars and the mass of the black hole.

Bradley Peterson

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