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Quasistellar Objects: Overview

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Quasistellar Objects: Overview

Quasistellar objects, or quasars, were defined originally as star-like objects of large redshift. Quasars are believed to be powered by the accretion of matter onto massive black holes at the centers of galaxies, a process that emits more energy than thermonuclear reactions. Today, quasars are considered to be the most luminous members of the general class of objects called active galactic nuclei, or AGNs. Quasars are the most luminous objects in the universe.

This article begins with a brief history of the discovery of quasars. Next it describes their main properties and the concepts that have been developed to explain them. It continues with a description of their nature and theoretical models. Then additional properties and topics are considered: absorption lines, host galaxies, and luminosity functions and evolution.

History

In 1960 Mathews and Sandage identified the radio source 3C 48 (the 48th object in the 3rd Cambridge catalog of radio sources) with a star-like object of 16th magnitude. Its optical spectrum showed unusual emission lines that could not be identified, and the object was considered to be a radio star, more of which were identified in the course of their work. In 1962, Hazard, Mackey and Shimmins established an accurate radio position for another source, the BRIGHT QUASAR 3C 273, by observing the object as it was being occulted by the Moon. Schmidt used this position to identify 3C 273 with a 13th magnitude star-like object (figure 1), whose spectrum also displayed unusual emission lines. Schmidt subsequently realized that the emission lines could be identified with lines from hydrogen and oxygen redshifted by 15.8% of their rest wavelength. A redshift of 0.158 was unprecedented for such a bright object. If the redshift arose from the expansion of the universe, it meant that 3C 273 was about two billion light-years distant, according to the Hubble law, in which the redshift of objects increases in proportion to their distance. Furthermore, the combination of the observed brightness of 3C 273 with the inferred distance meant that it had an intrinsic luminosity 100 times that of an entire galaxy like the Milky Way.

Following Schmidt's work, it was immediately realized that the redshift of 3C 48 was 0.37. By 1965, 3C 9 was found to have a redshift of 2.01, well in excess of the 0.46 value for 3C 295, the most distant galaxy known at the time. It had taken more than 30 yr of work on galaxies with the largest telescopes in the world for astronomers to push the limit of the observable universe to the distance of 3C 295. Only 2 yr after the discovery of quasars, the maximum observed redshift had increased

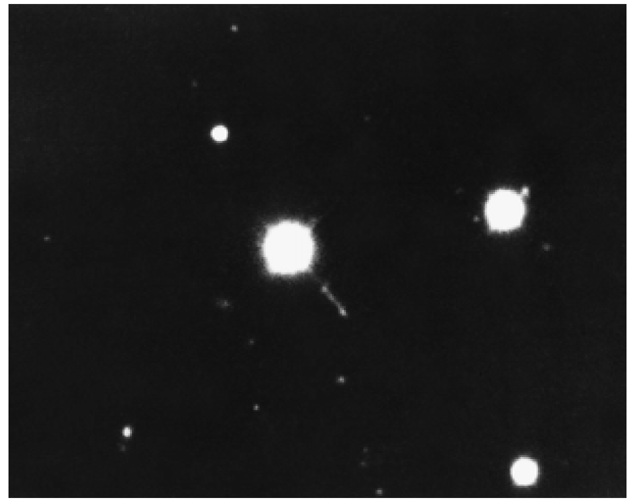

Figure 1. Optical image of 3C273. The object looks stellar in this image except that it is accompanied by a jet of radiation extending to the lower right. (Credit National Optical Astronomy Observatories/National Science Foundation. Copyright Association of Universities for Research in Astronomy Inc (AURA), all rights reserved.)

by more than a factor of 4. The light from 3C 9 had taken 80% of the age of the universe, or more than 10 billion years, to reach Earth. The ability to observe objects at redshifts greater than 2 meant that astronomers could probe back in time to within a few billion years of the big bang.

The unusual nature of quasars was compounded by the work of Smith and Hoffleit, who showed that 3C 273 varied significantly in brightness on timescales of months. This variability indicated that the characteristic size of the emission region was light-months and led immediately to the question, how could such a small object produce more light than an entire galaxy, with a typical size of 100 000 light-years?

To summarize, quasars revolutionized astronomy in the 1960s for two reasons: (1) they pushed back the limits of the observable universe significantly in both distance and lookback time and (2) their compact size and great luminosities could not be explained in terms of the stars and galaxies known at the time. Quasars opened new frontiers in cosmology and stimulated the development of a new subject—relativistic astrophysics.

Main properties and concepts

The main observed properties of quasars are the following.

1. Nuclei that appear starlike in optical images. Extended emission can now often be detected around the nucleus, and jets extending away from the nucleus are occasionally seen.
2. Spectra showing broad emission lines with widths greater than observed in normal galaxies and a range

of ionization broader than seen in typical nebulae ionized by stars.
3. Structures in quasars with observable radio emission that range in angular extent from m arcsec to tens of arcsec. The most compact structures are often observed to expand on timescales of years.
4. Radiation of similar power at energies ranging from γ-rays to the far-infrared (100 μm) region of the spectrum, with a decrease in energy at radio frequencies.
5. Redshifts, z, of spectral features ranging from 0.1 to 5.
6. Variability in brightness at different wavelengths on timescales as short as days to weeks.
7. Luminosities as high as 10^{14} Suns.
8. Total energy in high-energy electrons in the region of radio emission that can exceed 10^{60} erg.

Additional information about these properties and the concepts they imply about the nature of quasars follows below.

Redshifts

The large redshifts of quasars are one of their distinctive features, and the value of the greatest known redshift, z, continued to increase after 1965, surpassing $z = 3$ in 1973 and $z = 4$ in 1987. The maximum value reached $z = 4.9$ in 1991, and an object at $z = 5$ was discovered in the first stages of the Sloan Digital Sky Survey in 1998 (see QUASISTELLAR OBJECTS: SURVEYS). The great majority of quasars, however, have redshifts less than 2.5. This occurs for two reasons: (1) such quasars are easier to find because they are brighter in the ultraviolet than most stars and (2) they are intrinsically more numerous than quasars with $z > 2.5$. The low-redshift limit of quasars is normally set at 0.1 because objects at lower redshift are usually resolvable as galaxies and are cataloged as ACTIVE GALACTIC NUCLEI.

In addition to providing our first view of the universe at $z > 0.5$, quasars also proved to be valuable cosmological probes because they were luminous enough to yield clues on the properties of matter along the line of sight back to the Earth (see discussion on absorption lines below and in more detail in QUASISTELLAR OBJECTS: INTERVENING ABSORPTION LINES).

Variability

Observations indicate that variability is a common feature of quasars and most quasars are believed to show variations in light at the 10–40% level over timescales of months to years. Furthermore, variations are observed in the strength and shape of emission lines and in continuum emission at x-ray, ultraviolet and radio wavelengths. The variations are irregular in nature, with periods of flaring and relative quiescence being intermixed. Some objects, which are called BLAZARS, show variations in light on timescales as short as 1 day (see BL LACERTAE, BL LACERTAE OBJECTS and AGN: VARIABILITY).

Variability provides powerful tools for determining the inner structure and nature of quasars. When the central source itself varies in brightness, the effects of the variation propagate outward with time and produce changes in, for example, the emission line spectra and continuum radiation from the material surrounding the central source. In the case of blazars, we are seeing almost directly down the axis of the jets of material that are being ejected from the central regions. By following how the radiation from the jets varies at different wavelengths with time, we are able to infer the physical conditions and processes that are occurring in the jets.

Observations of the variability of quasars carried out at different wavelengths in intensive campaigns and also in programs extending for years have provided some of the most direct information on the nature of the inner regions in quasars and AGNs. These programs have shown that the emission line regions are considerably smaller and closer to the central source than was originally thought.

Continuum emission and multi-wavelength observations

Quasars emit radiation strongly in bands ranging from γ-rays and x-rays to the far infrared (100 μm). The amount of energy emitted in each band by most objects is remarkably similar, in contrast to normal thermal radiation from stars, which is much more peaked and restricted in wavelength. For example, most stars are cool and are faint at ultraviolet wavelengths. In contrast, most quasars with redshifts less than 2.5 are bright at ultraviolet wavelengths, a property that is very helpful in distinguishing them from the more numerous stars that are found in sky surveys.

Although quasars were discovered through their radio emission, about 90% of quasars do not emit strongly at radio wavelengths and are classified as radio quiet. Radio-loud quasars are typically 100 times brighter at radio wavelengths than radio-quiet quasars.

The continuum emission in quasars appears to arise from a combination of thermal and non-thermal processes. For the latter, synchrotron emission from relativistic electrons produces the lower-energy radiation. The x-ray and γ-ray emission may come from the inverse Compton scattering of lower-energy photons by high-energy electrons, although thermal mechanisms may also play a part in x-ray emission. In any event, the continuum radiation from quasars demonstrates that some very energetic processes are involved. Furthermore, the continuum radiation at the highest energies tends to show the most dramatic variability and the shortest timescales, which is another indication of the extreme conditions that exist near quasars.

Emission lines

The emission line spectra of quasars (figure 2) are characterized by the large widths of the lines and wide range of ionization. The full widths at half-maximum of the emission lines are typically 5000 km s^{-1} and range from about 500 km s^{-1} to greater than 10 000 km s^{-1}. Full widths at the base of the lines can exceed a tenth the speed of light.

The widths are produced by motions of gas in the emitting region, where a mixture of infall, rotation and ejection probably occurs. The widths are consistent with the emission region being at a distance of light-months to a few light-years from a central black hole.

One of the most striking observational properties of the spectra of quasars and AGNs is the anticorrelation of the strength of the C IV emission line at 1550 Å and the continuum luminosity, that is the emission line is observed to be weaker relative to the continuum in more luminous objects. This relation, which is called the Baldwin effect, is perhaps the most prominent observed correlation that has been found for quasar and AGN spectra. It is important for two main reasons: (1) the clues it provides about the nature of the emission line region and central source and (2) the potential it offers for using quasars as cosmological probes at high redshifts.

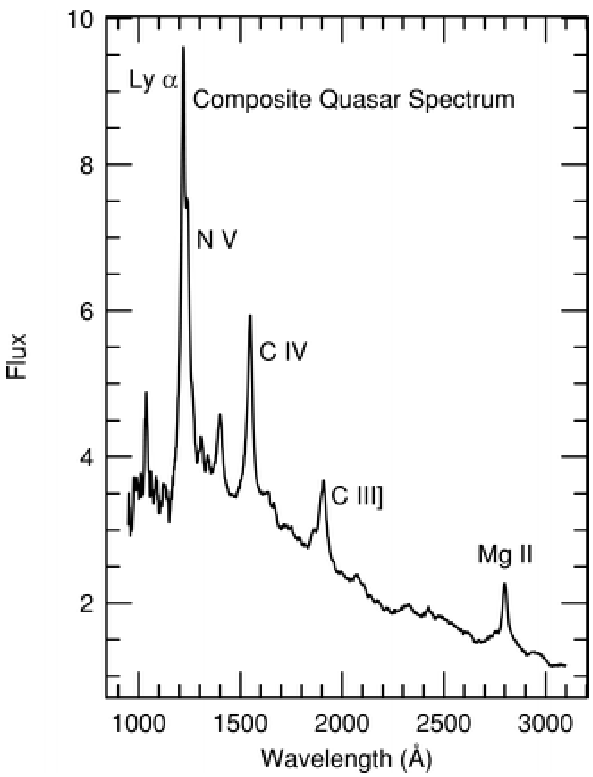

Figure 2. A composite quasar spectrum covering the ultraviolet region of the spectrum. It shows strong emission lines from hydrogen, carbon, nitrogen and magnesium. (Credit Francis P *et al* 1991 *Astrophys. J.* **373** 465.)

The strongest emission lines in quasar spectra come from hydrogen, carbon and magnesium, with lines of nitrogen, oxygen, iron and other elements also being visible. The observed levels of ionization range from neutral for hydrogen and oxygen up to five-times ionized oxygen and even more highly ionized iron. The range of ionization is another indicator of the strength of the non-thermal continuum radiation in quasars and its extent to high energies.

Although it is difficult to make a reliable determination of the chemical abundances in quasar emission line regions, results to date indicate that the abundances are similar to those observed in present-day stars and nebulae, even in quasars at the highest redshifts. This is a striking result when one considers that the most distant quasars correspond to cosmic times of 1 or 2 billion years after the big bang. Except for hydrogen, all the elements mentioned above originate in the thermonuclear reactions that occur in stars. The abundances of these elements increase with cosmic time as successive generations of stars complete their evolution. When stars die, they return part of their newly produced elements to interstellar space, and the next generation of stars forms from the enriched material.

Thus, the apparently normal abundances of the elements in high-redshift quasars implies that they were preceded by substantial stellar activity in the early universe.

Nature

The prodigious luminosities of quasars in combination with their small size led theorists to consider gravity as their energy source immediately on their discovery. It was realized that normal stars and thermonuclear reactions were entirely insufficient to produce the observed properties of quasars. However, the required gravitational potential energy could only be extracted if quasars contained compact objects with masses of a hundred million Suns and sizes about that of the solar system. In addition the gravitational field of such objects was so strong that the effects of general relativity would be dominant in their vicinity. Since that time, gravity has remained as the consensus source of energy for quasars, although the concepts of the nature of the central source have changed considerably. For example, supermassive 'stars', were originally postulated as the central objects in quasars, but enough difficulties were found with such ideas that they were soon abandoned.

Subsequently, it was realized that BLACK HOLES were the most likely central engines of quasars. A black hole was an object with gravity so strong that not even light could escape from its surface. The widths of the emission lines in quasars and estimates of the size of the emission line region suggested that the central mass was about 10^8 Suns. Such objects would not be able to support themselves against the pull of their of their own gravity, and they would collapse to form a black hole. The collapse could liberate 10% or more of the rest energy, mc^2, of the object, that is, more than 10 times the energy of the thermonuclear reactions that occur in stars. Similarly, any material later captured by the black hole would liberate the same fraction of rest energy. This of course provided an explanation for the energies found in quasars. As a result, quasars stimulated much work on the origin and nature of black holes and the detailed processes of how the observed energy could be obtained from them.

Today, the working hypothesis for quasars and AGNs is that massive (10^6–10^9 solar masses) black holes exist at their centers. The radiated energy we detect from them comes from matter being accreted onto the black hole. According to general relativity, the radius of a black hole is 3 km per solar mass, and the radii of black holes in AGNs and quasars range from a few solar radii to 20 times the distance of the Earth from the Sun.

It is most likely that much of the matter surrounding the black hole is in the shape of a disk. The matter in the disk orbits the black hole and moves inward as it loses angular momentum from some source of viscosity in the disk. The inner edge of the disk may extend to within a few radii of the central black hole. The gas in the inner regions of the disk is expected to be hot enough, about 10^{4-6} K, to account for the thermal component of the continuum radiation at ultraviolet wavelengths.

The x-ray observations of quasars provide evidence of the existence of a corona of energetic particles above the accretion disk. The x-rays may be produced by upscattering of the ultraviolet photons from the disk on the energetic particles via the inverse Compton process. Some x-rays may also be produced in shocks located farther from the central source.

Jets of beamed radiation are also an important feature. They are frequently observed in radio-loud quasars and, as in the case of 3C 273, sometimes are seen at optical wavelengths. The jets are thought to be accelerated electromagnetically and ejected along the rotational axis of the black hole. They can be moving at relativistic speeds and contain high-energy particles, such as the relativistic electrons that produce the radio emission through the synchrotron process. The radio emission in the 3C 273 jet is located several light-years distant from the central source.

A striking feature of jets in some radio sources is that repeated observations on the smallest angular scales with radio interferometers show them to be moving outwards at speeds that appear to be several times greater than the speed of light. This of course would violate a basic limit of relativity. The most satisfactory explanation for this paradox is that the jets are moving at speeds near that of light in the direction of the Earth. In this case the apparent time interval in the expansion motion of the jet appears smaller than it really is because of the motion toward the Earth. See the article on SUPERLUMINAL MOTION for more information.

The emission line spectra of quasars indicate that there are also gas clouds surrounding the black hole. The clouds occupy about 10% of the volume of the region where the broad emission lines are produced. The broad emission line region in quasars can extend to several light-years from the black hole.

Understanding the nature of the inner regions of quasars and the central black holes continues to be an important subject of research both observationally and theoretically. Specific topics include the formation of black holes and their relation to the formation of galaxies, the role that galaxy interactions play in providing the fuel supply of gas for accretion onto the black hole and how quasars evolve in time and what is their relation to the inactive black holes now being observed in the centers of nearby galaxies.

Alternative theories

One of the first alternative explanations for the large redshifts of quasars to be investigated was gravitational. If the emission arose near a compact massive object with a sufficiently strong gravitational field, then the emission lines could exhibit large redshifts. However, it was realized almost immediately that such a hypothesis was inconsistent with the widths and other properties of the emission lines, and the hypothesis was ruled out.

Another hypothesis was that quasars were being gravitationally lensed and thus appeared much brighter than they really were. Interestingly, many years after this idea was proposed, some quasars were discovered to be lensed, but they are only a small fraction of the total.

From observations of the apparent associations of quasars with galaxies of much lower redshift, Arp has challenged the concept that quasar redshift arise from the cosmological expansion of the universe. In this picture, the redshifts arise from some other, non-cosmological effect whose nature has yet to be determined.

Subsequent observations, however, have shown that quasars do reside in galaxies. In the cases where it has been possible to measure the redshifts of the host galaxies, they agree with the redshifts of the quasars. Furthermore, low-luminosity quasars and luminous Seyfert galaxies overlap in luminosity and show a general continuity of properties.

Today, it is generally accepted that the large redshifts of quasars do arise from the expansion of the universe and that they are at the distances indicated by the redshifts.

A different approach has been taken by Terlevich and collaborators, who have proposed that starbursts, intense episodes of star formation, can account for quasars. In this case energy from hot, young stars and the supernova explosions that occur at the end of their evolution provides the radiation and spectral properties observed in quasars and AGNs. While there are abundant observations showing that starbursts are common in regions around AGNs and may well be related to the processes that fuel the central object, the starburst model has great difficulty in accounting for the most luminous quasars and for the rapid variability in x-rays that is observed in AGNs. Furthermore, the observational evidence for black holes in nearby galaxies has become increasingly strong.

Additional topics

Absorption lines

Absorption lines were detected in quasars within a few years of their discovery and were initially believed to be rare. However, with improved sensitivity and spectral resolution, it became clear that absorption lines were present in all quasars with redshifts 2 and greater. A contributing factor to their presence was that ultraviolet, ground-state lines were being redshifted to wavelengths where they could be observed with ground-based telescopes. Today, the study of quasar absorption lines is a major topic and the article on this subject should be consulted for more details.

Absorption lines may be placed in three categories according to the distance of the absorbing gas from the central emission source of the quasar: (1) intrinsic systems, (2) associated systems and (3) intervening systems.

Intrinsic systems arise close to the quasar itself. The most conspicuous members of this class are the broad absorption line (BAL) quasars, whose spectra show broad troughs of absorption on the short-wavelength side of the Lyman α line of hydrogen and such high-ionization lines as C IV λ1549 and N V λ1240, for example. The troughs indicate outflow velocities that can exceed 30 000 km s^{-1}. BAL features are seen in about 10% of high-redshift quasars, a value that gives an indication of the average covering factor of the outflowing gas.

Associated systems show absorption features from elements such as hydrogen, carbon and magnesium. They have redshifts close to that of the emission lines in quasars but are much narrower. They are believed to arise in gas associated with the host galaxy of the quasar or the environment in which the host galaxy resides, which might be a group or cluster of galaxies.

Intervening systems have redshifts smaller than the emission lines in quasars and arise in clouds of gas unrelated to the quasar that lie along the line of sight to the Earth. In this case, the quasar serves as a background beacon that enables the study of otherwise invisible gas. The sight lines to quasars probe representative samples of intergalactic space, and absorption line spectra provide an unbiased way to determine the nature and distribution of the gas. Studies of absorption lines in quasars have provided crucial information about gas in the high-redshift universe. Intervening systems may themselves be classified in three groups according to the column density of the absorbing gas: (a) damped Lyman α systems, (b) intermediate (metal line and/or Lyman limit) systems and (c) the Lyman α forest.

Damped Lyman α systems represent the highest column densities, typically in excess of 10^{20} neutral hydrogen atoms cm^{-2}, and are so called because absorption is so strong that the damping wings of the line are seen. Such systems are thought to occur when the line of sight passes through a disk galaxy. Some may also arise in dense clouds or filaments of intergalactic gas at high redshift.

Damped Lyman α systems, because of their high column densities, also exhibit absorption lines from heavier elements such as carbon, silicon, magnesium and iron, with additional elements being detected in the most favorable cases. Analyses of these lines indicate that the abundance of metals in the systems is about one-tenth of the solar value. This is consistent with our understanding of the chemical evolution of galaxies, in which the abundance of metals increases with cosmic time owing to the continuing enrichment of the interstellar medium by supernovae and red giant stars as they complete their life cycle. Damped Lyman α systems can only be observed from the ground for redshifts greater than 1.8, which corresponds to a lookback time of approximately 80% of the age the universe.

Intermediate systems, with a characteristic column density of 10^{17} neutral hydrogen atoms cm^{-2}, also show absorption lines from elements such as carbon, magnesium and other metals plus a discontinuity at the Lyman limit of hydrogen. They are commonly attributed to the halos of galaxies. Their metal abundances range down to 1% of the solar value, indicating that they have had less chemical enrichment than the gas in damped Lyman α systems.

The Lyman α forest lines are the most numerous and ubiquitous absorption features and are attributed to clouds of gas in the intergalactic medium. They are seen in a range of column densities beginning at the limit of detectability around 10^{12-13} neutral hydrogen atoms cm^{-2} and extending up into the range of the intermediate systems. Their number density increases with redshift; by redshift 4, the integrated effect of absorption from the Lyman α forest produces a significant depression of the flux shortward of the Lyman α emission in quasar spectra. Observations of the Lyman α forest are used to deduce the state of ionization of the intergalactic medium. Much of the ionizing flux at high redshift is produced by quasars. The data are also important for understanding the formation of structure in the universe.

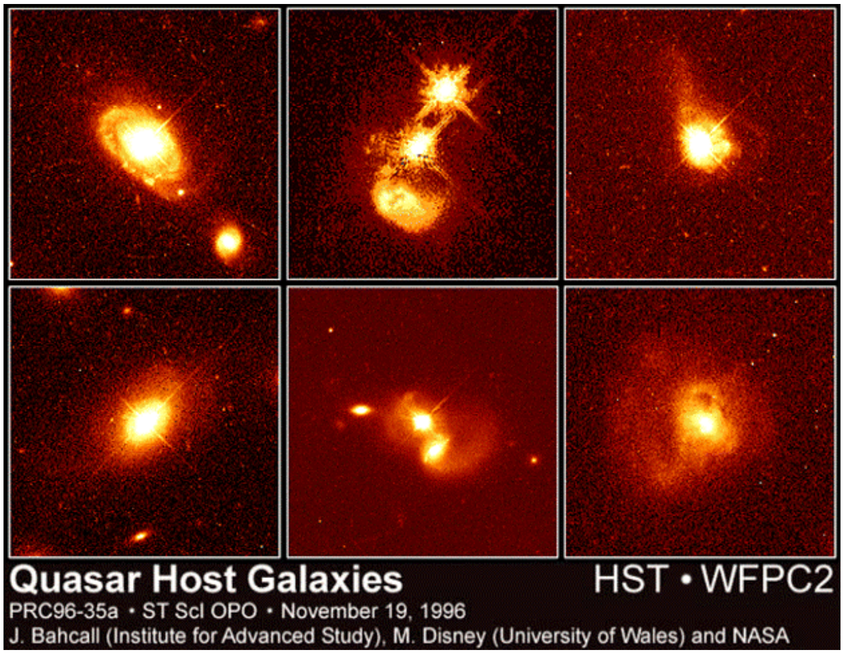

Figure 3. A sample of images showing the host galaxies of quasars. The hosts can be normal-looking spiral and elliptical galaxies (left panels) but are frequently seen to be interacting or merging galaxies (center and right panels). (Credit J Bahcall, M Disney, NASA. This image was created with support of Space Telescope Science Institute, operated by the Association of Universities for Research in Astronomy, Inc from NASA contract NAS5-26555, and is reproduced with permission from AURA/STScI.)

Host galaxies

The regions immediately around quasars are difficult to observe because of the glare from the central source, which is why quasars were originally called star-like objects. However, with improved observations, extended emission began to be detected around quasars. In the meantime the realization was developing that quasars, Seyfert galaxies and other active galactic nuclei were members of the same family. One of the main differences among the different classes of objects was the luminosity of the central source, and the host galaxies with low-luminosity nuclei were much easier to study.

The excellent image quality and spatial resolution of the Hubble Space Telescope have enabled a significant advance of our knowledge of quasar host galaxies (figure 3). Results to date for low-redshift objects show that quasars occur in elliptical, spiral and interacting galaxies, with some of the latter appearing very disturbed by the interaction. On average, the host galaxies are brighter than normal field galaxies. The radio-loud quasars tend to occur in elliptical or interacting galaxies. The radio-quiet quasars can occur in elliptical or spiral galaxies. These results are in contrast to the situation for lower-luminosity AGNs, where there are stronger tendencies for radio-quiet objects to occur in disk galaxies and radio-loud objects in ellipticals.

The study of host galaxies is important to improving our understanding of how both galaxies and quasars form and evolve. The quasar is in the nucleus of the galaxy and represents the endpoint of the process that produced the central concentration of matter in the galaxy. How a massive black hole formed and grew from the central concentration remains an important research question. At the same time, for the black hole to be visible and attain the luminosity observed for bright quasars, it must accrete several solar masses of material per year. What causes this inflow of matter from the outer parts of the galaxy to the nucleus is also an important topic. It is thought that the interaction of two galaxies, that is their collision or near collision, can produce enough disruption to the orbit and angular momentum of stars and gas to produce the inflow, but the details of the process are not yet fully understood.

Luminosity functions and evolution

The luminosity function of quasars is the distribution of their volume density as a function of luminosity and redshift. As with galaxies, the number density decreases steeply at the highest luminosities. At low luminosities the slope of the function is smaller than at high luminosities, so the rate of increase of objects slows with decreasing luminosity.

Luminosity functions are among the most basic parameters in astronomy and provide a basis for determining the amounts of matter in different forms in the universe.

One of the most striking properties of quasars is the evolution of their luminosity function with redshift. This was first noticed by Schmidt, who realized there were too many quasars at high redshift in early surveys if the space density of objects were constant. Interpreted as density evolution, the space density of luminous quasars is more than a thousand times greater at $z = 2$ than in the local universe. An alternative explanation is that quasars were brighter at high redshift than at present.

At redshifts greater than 3, there is considerable observational evidence that the space density of quasars declines steeply. A logical interpretation of the results (figure 4) is that we are seeing back to the epoch of peak quasar activity. Alternatively, clouds of dust at high redshift could be blocking our view of more distant quasars. For example, such clouds could be associated with star formation regions in the host galaxy of the quasar. However, the best information currently available indicates that dust is an important factor for some types of quasars but does not account by itself for the decline in space density at high redshift. In any event, the most distant objects now known in the universe are galaxies, the first time this has happened since 1965. Although this may be a coincidental result, it is another indication that quasars at redshifts greater than 5 are genuinely very rare objects.

Current observations of quasars and distant galaxies are consistent with bursts of star formation occurring in galaxies before the quasar activity builds up to its peak around redshift 2–3. As was mentioned earlier, the gas in the emission line regions of distant quasars appears to have relatively normal abundances of elements heavier than hydrogen, which implies that the gas has been enriched by massive stars before reaching the quasar. Furthermore, it takes time for a supermassive black hole to attain the masses needed for quasars, time that allows for a few generations of massive stars to complete their evolution. For reference, the age of the universe is only about a billion years at redshift 5.

Subsequently, the overall rate of star formation in the universe reaches a peak as galaxies continue to form and assemble. After that, both quasar activity and star formation rates decline until they reach the values observed today in the local universe. Both declines are probably related to galaxies completing their formation and assembly. In addition, the rate of interactions and mergers of galaxies decreases as the universe continues to expand. As a result less material is available (1) to fall to the central regions of galaxies and fuel the massive black holes and (2) to form stars.

In this picture, the quiescent black holes that today are found to be ubiquitous in nearby galaxies are the products of the spectacular galaxy formation process and quasar activity that occurred in the first third of the history of the universe.

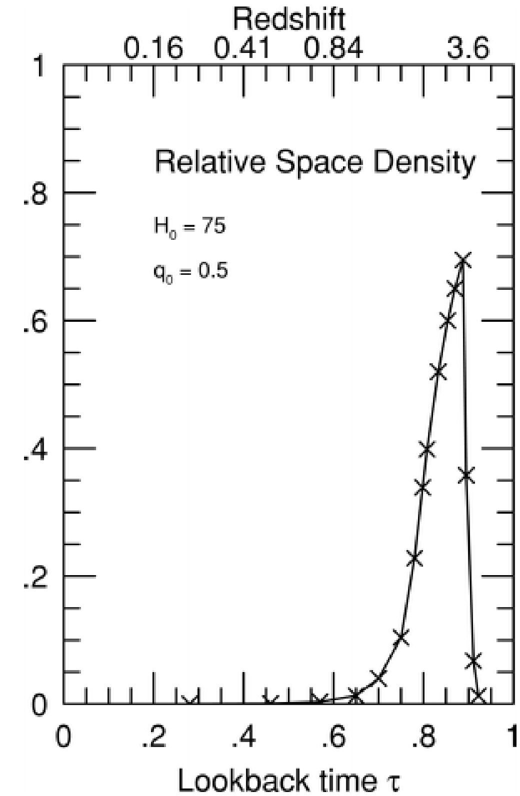

Figure 4. The evolution of the space density of luminous quasars as a function of cosmic lookback time, expressed as a fraction of the age of the universe. The space density shows a strong peak at 0.85, when the universe was 15% of its present age. (Credit Warren S, Hewett P and Osmer P 1994 *Astrophys. J.* **421** 412.)

However, the picture is but a sketch and is in need of both development and confirmation. We may expect significant progress in the near future on several fronts.

- Large new surveys for quasars that are being carried out at optical and radio wavelengths, such as the Sloan Digital Sky Survey, the Australian 2dF Survey and the FIRST radio survey, will increase the number of known quasars by a factor of ten. (In June 2001, two quasars with redshifts of 6.0 and 6.2, the most distant objects ever observed in the universe were identified in the Sloan Digital Sky Survey.)
- The new generation of large telescopes with 8–10 m apertures that has come into operation and space observatories such as Chandra and XMM that will soon be launched provide powerful tools for observing quasars with significantly more sensitivity and resolution at optical, infrared and x-ray wavelengths than has been available previously.
- Advances in theoretical modeling and the continuing increase in computing power will enable significant progress in interpreting the new observations and in modeling the inner regions of quasars and key processes such as accretion.

Thus, the prospects for improving our understanding of how quasars form and evolve and for determining their relation to galaxies are very bright.

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