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Quasars and Gravitational Lenses

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Summary. Despite the expenditure of large amounts of telescope time and other resources, most of the fundamental questions concerning quasi-stellar objects (quasars) remain unanswered. A complex phenomenology of radio, infrared, optical, and x-ray properties has accumulated but has not yielded even a satisfactory classification system. The large red shifts (distances) of quasars make them very valuable tools for studying cosmology and the properties of intervening matter in the Universe through observations of absorption lines and gravitational lenses.

Even though the discovery of quasars (objects with the highest red shift and probably the most distant and luminous sources in the Universe) was one of the most exciting events in the recent history of astronomy (*1*), in many ways their study has proven to be one of the least successful enterprises in astronomy during the past two decades. Despite intensive and systematic observations in every available wavelength range, few if any of even the simplest and most basic questions about quasars can be answered with certainty. For the key question of the nature and structure of the central energy source, progress during the past 15 years is barely discernible. Similarly, in spite of their large red shifts, quasars have shed little light on cosmological problems. The enormous investment of observational resources in quasar studies has led to the discovery of ~ 3000 quasars and has generated a large and complex body of empirical and phenomenological information, but even in this research effort the situation is far from satisfactory. Selection biases may still be seriously distorting our empirical assessment of quasar properties. No well-defined and generally accepted morphological classification system has appeared. Very few clear correlations or regularities in quasar properties have been observed.

Notwithstanding these difficulties and disappointments, the enthusiasm of astronomers for the study of quasars has not declined. Observational work continues at an undiminished rate, and theoretical attention is increasingly focused on a particular "best guess" model (*2*) for the nature of the central energy source. Moreover, recently there has been important progress in some areas of quasar research. On the observational side, x-ray observations of significant samples of quasars are now available (*3*), an all-sky bright quasar survey has been carried out (*4*), and new slitless spectral techniques (*5*) have greatly increased the number of known radio-quiet quasars. Our knowledge of the population statistics and statistical evolution of quasars (*4, 6*) has attained a new level of sophistication and reliability, subject to the highly likely, but not quite certain, hypothesis of cosmological red shifts. Perhaps the most dramatic results of quasars studies do not bear on quasars at all but rather on the intergalactic gas clouds and gravitational lenses through which we view some quasars. In these studies, the quasar simply acts as a convenient background light source which allows observations of absorption lines or gravitational deflections due to intervening objects. Over all, despite the slow growth in our understanding of their physical natures, quasars still provide the best available probe of the most distant observable regions of the universe.

In this article I present a selective review of the current state and apparent prospects of various areas of quasar research. The choice of topics and emphasis reflect my personal research interests to some extent.

Empirical Properties

Quasars have been detected in essentially every wavelength band used by astronomers from radio to γ-rays. Extensive radio, infrared, optical, and x-ray surveys have been carried out. Thus the purely empirical properties of quasars are fairly well known.

Quasars are essentially defined by their optical properties to be unresolved or nearly unresolved (that is, having nearly all of their flux in a component unresolved at the $\sim 1''$ limit imposed by atmospheric blurring) objects with spectra containing highly red-shifted emission lines (*7*). These red shifts ($= \Delta\lambda/\lambda$) generally lie in the range from 0.1 to nearly 3.8 with many values near 2.0. If not completely stellar (unresolved) in appearance, quasars generally show faint and frequently asymmetric halos with sizes of the order of a few arcseconds. In addition to these defining optical features, many quasars share several other optical characteristics. The observed emission lines may generally be identified with resonance lines of hydrogen or of ions of heavy elements present in high cosmic abundance. The two most common strong quasar emission lines are Lyman-α (hydrogen) and C IV (triply ionized carbon) with rest wavelengths in the vacuum ultraviolet. In addition to exhibiting large red shifts,

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quasar emission lines are generally very broad with widths up to several percent of their observed wavelengths. The continuum emission from quasars is usually a nonthermal spectrum with strong ultraviolet and infrared excesses relative to a thermal Planck spectrum; in many cases the flux per unit frequency may be approximated by a ν^{-1} power law, although there are wide variations about this mean slope. Almost all quasars show slow (over years) continuum flux variations of a few tens of percent, and a few vary rapidly (in as little as a few days) by factors up to 100 or more. Large and variable polarization has also been seen in some of the optically active quasars. Finally, most quasars of high red shift show a multitude of narrow and weak absorption lines when observed at high spectral resolution with good signal-to-noise ratio. It is only possible to identify these lines by associating them with a number of discrete objects each having a different red shift (in almost all cases smaller than the emission-line red shift) through which the quasar continuum source is being seen.

Only a small fraction ($\sim$ 3 percent) of quasars are radio sources; however, radio quasars are strongly overrepresented among known (catalogued) and well-studied quasars because, until fairly recently, the optical identification of radio sources was by far the easiest way to locate quasars seen in projection among the ordinary stars in our Galaxy. Those quasars that are radio sources are frequently very powerful and, in fact, number among the brightest radio objects in the sky. Radio quasars generally contain a compact central source with structure frequently extending down to scales of milliarc-seconds, emitting a flat (spectral index ~ -0.25) power-law spectrum over a wide range of frequencies. Strong variability both in flux and in milliarc-second image structure on a time scale of months to years is common. In many cases the central source will be flanked by much larger nonvariable double radio lobes with a steep spectrum, reminiscent of typical radio galaxy structure.

X-ray surveys of quasars made with the Einstein satellite (*3*) have established that many quasars are strong x-ray sources and that their combined emission must account for at least a modest fraction of the cosmic x-ray background. There are indications in the data that quasar x-ray emission may be well correlated with optical emission, although selection effects and other difficulties with the x-ray sample cast some doubt on this and other statistical inferences about x-ray emission (*8*).

Classifications

The complex phenomenology summarized above has given rise to a rather confused system of subclassifications for the sources generically known as quasi-stellar objects (quasar or QSO) and the apparently related phenomena of active galactic nuclei (AGN). Quasi-stellar radio sources (QSS) are quasars with detectable radio emission. BL Lacerta objects (BL Lacs) are quasar-like objects that show no or only extremely weak emission lines. Optically active quasars are those that show unusually rapid or large-amplitude light variations and strong optical polarization. N galaxies are essentially ordinary galaxies containing a quasar-like object, which dominates their total luminosity. Seyfert galaxies of type I are galaxies (usually spirals) containing a central object with optical properties much like those of a quasar though of sufficiently low luminosity that they do not dominate the total galaxy luminosity. Radio galaxies are galaxies (usually ellipticals) with radio emission properties like those of quasars although frequently without the central flat spectrum component. There are also various classifications based on details of the emission- or absorption-line spectra of quasars.

Unfortunately, these classifications are not mutually exclusive, distance-independent, or universally applied in any consistent way. Our understanding of the morphology of quasars and AGN has not yet reached a state analogous to the invention of spectral types for stars much less to the discovery of a "main sequence." The explanation for this unsatisfactory state of affairs is the absence of any strong or universal correlations or regularities in the empirical properties of quasars. There are a few intriguing hints such as the absence of radio lobes in BL Lacs and the correlation of variability with spectral steepness in the optical band but no sign of anything comparable to the Hubble sequence for galaxies. Of course, it is not necessary that quasars have any such regular morphology; nevertheless, its absence and the empirically rather meager definition of a quasar leave room for worry that a rather diverse set of physical phenomena might all have been lumped together (*9*).

Red-shift Distances and Population Statistics

Fortunately, it is not necessary to understand the nature of a class of astronomical objects in order to study its population statistics, that is, the mean number density, spatial distribution, and luminosity function (distribution function of luminosities in one or more bands) of the objects. What is necessary is to be able to measure the objects' distances. For quasars this is straightforward if one assumes that their red shifts are cosmological and give their distances via the Hubble law. On the other hand, if this assumption is not granted as a given, it has proven very difficult to establish by independent means. The study of quasars has been accompanied by a vigorous controversy over this point ever since it began (*10*). At present, there is no independent distance indicator for the vast majority of known quasars. Most quasars of low red shift are associated with faint objects which could be (and in some cases demonstrably are) galaxies of the same red shift (*11*), thus associating them with the well-established galaxy red shift–distance relation. A very few quasars of high red shift are constrained to be at large cosmological distances by gravitational lensing or spectroscopic line ratio arguments (*12*). On the other hand, a small but at least intuitively surprising number of quasars appear in the sky in the company of nearby galaxies of much smaller red shift (*13*). In short, although the controversy has not yet been decisively resolved, the cosmological interpretation of quasar red shifts remains observationally viable and scientifically productive. It will be assumed for the remainder of this article.

The most striking feature of quasar population statistics is the extremely rapid cosmic evolution apparent in the quasar luminosity function. Both the number density and typical luminosity of quasars appear to increase rapidly with increasing red shift, or, equivalent, light-travel look-back time (*4*). This evolution is most extreme for quasars of high optical luminosity; for instance, quasars with absolute blue magnitudes $M_B < -29$ (that is, at least 2000 times brighter than a typical normal galaxy) have a number density that changes by a factor of 2 in only about 3 percent of the age of the Universe. For more typical quasars with luminosities a factor of 10 to 20 times lower, this population half-life is up to over 5 percent. For AGN or quasars with luminosities comparable to that of a normal galaxy, this half-life is not reliably known but is probably at least a substantial fraction ($\gtrsim 1/4$) of the Universe's age; the data may even be compatible with no evolution for these objects.

The quasar luminosity function (the number of quasars per unit volume per unit luminosity interval) varies roughly as L^{-1} for luminosities corresponding to $M_B \gtrsim -26$ (less than roughly 100 typical galaxy luminosities) and then breaks more steeply downward for greater luminosities. At low red shifts the high-luminosity tail of the luminosity function is somewhat steeper than L^{-6}, but this slope rapidly flattens at higher red shifts as a result of the differential density evolution described above.

Another striking feature of quasar population statistics is the absence of significant numbers of quasars with red shifts above ~ 3.5 (*14*). Only a handful of objects with greater red shifts are known at all, and the upper limit on the comoving density of quasars in the red-shift range 3.7 to 4.7 is below the measured density for the range 3.0 to 3.5 by at least a factor of several. The combination of this red-shift cutoff with the steep density evolution described above implies a rather special "quasar epoch" in the evolution of the Universe. Taken literally, it implies that number density versus time for luminous quasars consists primarily of a very narrow spike with a full width at half maximum well less than 10 percent of the Universe's age. If the large red-shift cutoff cannot be explained as a result of dust obscuration (*15*) or some as yet undiscovered selection bias, the explanation of this extraordinary evolutionary behavior will stand as a major challenge to any comprehensive theory of quasars. Some would even argue that it mitigates against the cosmological interpretation of the quasar red shifts.

Rather less is known of quasar luminosity functions and evolution as measured in bands other than the optical. The radio luminosity function appears to be a featureless power law of index approximately −3 for QSS (*16*). There are also indications of strong density evolution for QSS (*17*). There are somewhat conflicting indications that x-ray luminosity is well correlated with optical luminosity and that the average x-ray–to–optical luminosity may be decreasing with increasing red shift (*3, 18*).

Nature of the Energy Source

On the basis of the preceding comments, the reader might expect that astronomers have no idea of the fundamental nature of quasars. This is not the case; in fact, there is a widely agreed upon "best guess" model. In this model a quasar is thought to be a massive (~ 10^7 to 10^9 $M_\odot$, where $M_\odot$ is the mass of the sun) black hole surrounded by a disk of accreting gas and located in the nucleus of a large galaxy (*2*). The basic power source is the gravitational potential energy released by the infalling gas. The primary sources of radiation are thermal radiation from the disk, coherent high-energy phenomena very near the black hole, and perhaps magnetic phenomena (that is, flares) in the differentially rotating accretion disk. Collimated beams of magnetized relativistic plasma are thought to be produced by the confining effects of the inner edge of the accretion disk on the radiation emitted near the black hole. In this model the radio emission is identified with synchrotron radiation in this plasma; the optical and near-optical continuum is the thermal disk radiation (with its spectral shape masked by the strong radial variation of temperature) or possibly also synchrotron emission; x-rays are generated by inverse Compton scattering in the plasma; and emission lines are produced in a large surrounding cloud of photo-ionized gas. The observed narrow absorption lines are generally attributed to intervening clouds of intergalactic gas that are not directly associated with the quasar. The required accretion rate for this model is ~ 1 $M_\odot$ per year for a typical quasar and perhaps 100 times as much for the most extreme objects. The source of this gas is uncertain but might include primordial gas in the galactic nucleus, mass lost by stars in the course of their normal evolution, stars tidally disrupted by the black hole, and clouds of gas accreted by the galaxy through collisions with other galaxies or directly from the intergalactic medium. Variability is the result of changes or instabilities in the accretion flow in this picture. Evolution in the number or luminosity of quasars with cosmic epoch is explained (poorly?) by changes in the mean availability of gas (fuel) in galactic nuclei with time.

This standard model of quasars owes its popularity to several strengths. First, it explains at least qualitatively most of the general empirical properties of quasars. Second, the discovery of SS433, a stellar system (~ 1 $M_\odot$) in our Galaxy, which displays in miniature many of the properties of quasars and which is almost certainly explained by a scaled-down accretion disk model, indicates that such systems can exist and that most of the relevant physical mechanisms can operate as required by the model (*19*). Third, essentially all models for quasars are forced to concentrate enough matter into a small enough volume that the eventual formation of a large black hole seems likely. Fourth, the standard model is perhaps more popular than is strictly scientifically warranted because it provides a convenient way of focusing and organizing the theoretical discussion of quasars between various investigators.

The standard model also has weaknesses. Chief among these is that it predicts very little and is of no real assistance in organizing or classifying the observed phenomenology of quasars. Another important point is that very few of the competing models for quasars can be eliminated by the data even though most of them were proposed soon after the discovery of quasars. The competition includes models for various types of discrete supermassive stars or pulsars and models involving dense clusters of objects of low (stellar) mass (*20*). Essentially any model that can hope to produce relativistic plasma and high-energy density radiation fields with reasonable efficiency remains in the running.

Absorption Lines and the Intergalactic Medium

Perhaps the most scientifically productive result of quasar studies to date has nothing directly to do with quasars nor does it depend on a knowledge of their physical natures although it does (again) depend on the association of their red shifts with cosmological distances. This is the study of clouds in the intergalactic medium through observation of the absorption lines they produce in the spectra of quasars of high red shift. This technique effectively allowed the "discovery" of the intergalactic medium, giving rise to a large and complex field. Only a bare summary of the main results can be given here.

At least two basic types of absorbing clouds have been discovered (*21*). The two types differ in their content of heavy elements, in their total number, and in their red-shift clustering properties. The rarer of the two types contains heavy elements at abundances that may approach solar values. The absorption red shifts of these clouds often occur in clumps with spreads of a few hundred to a thousand kilometers per second. Clouds of the second type are much more numerous but reveal themselves only by hydrogen Lyman lines, primarily Lyman-α. Typically they appear as a forest of narrow absorption features blueward of a quasar's Lyman-α emission line. They apparently are low in heavy-element abundance; the upper limit is uncertain, in that it depends somewhat on the clouds' ionization state, but is probably in the vicinity of a few percent of solar abundances. The red shifts of these Lyman-α clouds are distributed randomly and independently in any particular red-shift interval. The number density of Lyman-α clouds per unit comoving volume appears to increase slowly with increasing red shift but appears to be relatively constant from one quasar to another at any given red shift.

These two cloud populations are believed to be due to the interstellar medium of normal galaxies on the one hand and to perhaps primordial, isolated intergalactic clouds on the other (*21*). The number, high metal content, and red-shift clustering properties of clouds of the first type may be roughly explained if the interstellar medium in the outer regions of normal spiral galaxies is similar to that in our own Galaxy and extends to an effective radius a few times larger than that of the visible stars; there is some independent evidence that this may be the case (*22*). The absence of red-shift clustering in the Lyman-α clouds makes it impossible to associate them with ordinary galaxies for most (but not all) theories of the evolution of galaxy clustering. This fact, their low heavy-element abundance, and the change in their number density with cosmic time suggest that they are primitive and perhaps primordial objects, which may therefore provide information on the course of cosmic evolution.

Gravitational Lenses

The recent, though long predicted, discovery and the ongoing detailed study of gravitational lens systems among the quasars open the door for a wide variety of qualitatively new types of observations and may provide a major new tool for extragalactic astronomy and cosmology (*23*). In such gravitational lens systems, the line of sight to a distant quasar passes very near an intervening galaxy, cluster of galaxies, or other object. This results in a strong magnification, displacement, distortion, and in some cases fragmentation of the quasar's image due to the gravitational deflection of photons from the quasar by the intervening object. As in absorption-line studies, the physical nature of quasars is unimportant for gravitational lens studies; the quasar simply provides a convenient distant but bright light source.

In addition to the uses of gravitational lenses discussed below, it is well to recall that they do represent a fundamental physical phenomenon of some importance. Their existence was predicted (*24*) and their astronomical significance discussed (*25*) during the same period when the advent of modern physics led to the widely celebrated predictions of degenerate dwarfs, neutron stars, black holes, interstellar clouds, the microwave background radiation, and so forth. It is not impossible that gravitational lensing will someday also join this list in terms of its fundamental importance for astronomy.

The first major use for gravitational lensing is as a probe of the distribution of matter, particularly dark matter, both in the lensing objects themselves and along the line of sight out to the lenses. During recent years it has become increasingly clear that most of the mass density of the Universe and even much of the matter in individual galaxies must reside in some form that does not emit strongly (at least at any accessible wavelength) (*26*). The factor by which this dark material exceeds the mass density in ordinary stars, interstellar matter, and other detectable objects is not known but could be ~ 10 to 100. Discovery of the nature and detailed properties of this component of the Universe is generally recognized to be one of the most important problems in astronomy today. Gravitational lensing offers hope of addressing this problem in several new ways because it depends entirely on the space distribution of gravitating material between the source and the observer and not at all on any of its other properties. Specifically, observations of individual lens systems and the statistical properties of samples of lenses can be used in principle to determine the total masses of lensing galaxies, to characterize the distribution of dark matter in rich clusters, to discriminate between very different models for the nature of the dark material (for example, neutrinos versus very-low-mass, nonburning stars versus massive black holes), to detect a uniformly distributed component of the Universe's mass density, and even to identify specific condensed dark objects if such things exist.

A second major application for gravitational lens observations will be the determination of cosmological parameters. This possibility arises because the background cosmology in which lensing occurs determines the geometrical optics of the situation. Measurements of differential time delays between images in lens systems and the statistics of the properties of samples of lenses can be used to determine all the classical cosmological parameters (H_0, q_0, and Λ) (*27*) in principle. Moreover, the internal consistency of such determinations can be used to check the validity of the standard cosmological models. The possibility of measuring or at least placing limits on Λ is particularly good because lensing is much more sensitive to this parameter than other available astronomical observables.

A third possible application for gravitational lenses is to use them directly as lenses in a sort of natural telescope that will allow us to look much more deeply into space (in a few small patches of the sky) than would otherwise be possible. This possibility, which was first pointed out in 1937 (*25*), may in a few special situations improve the effective performance of our telescopes by a factor of several (at no additional cost!).

The reader will have noted the phrase "in principle" or the word "possible" in most of the critical sentences above and will realize that many of these potential applications of lensing will be quite difficult to realize. Indeed, some may be completely impractical even in the long term. Gravitational lenses are rare and hard to locate; so far, only five cases have been found among the ~ 3000 known quasars (though many could have been missed). Many of the idealized lensing tests such as the determinations of cosmological parameters may be confused by other astrophysical effects in reality. Many of the required observations will be practically difficult since they will require that faint objects be monitored with high resolution and good time coverage. Nevertheless, the questions that lenses might enable us to answer are so important and so difficult to attack by other means that the incentive for at least trying to overcome the problems will be great. One probably should not be too discouraged yet that work on the five known examples of lensing have not produced any breakthroughs [in fact, it can be demonstrated from the properties of 0957 + 561 that the matter in the rich cluster that forms part of that lens cannot be distributed like the galaxies (*28*)] for two reasons. First, ground-based observations do not have the resolution or sensitivity to objects of low surface brightness needed to clearly disentangle the quasar images from the lensing galaxy and to determine the positional and structural parameters of the latter accurately; Space Telescope will decisively relieve this problem in a few years. Second, only five cases have been studied so far (only two extensively); the first five pulsars discovered did not teach us much about neutron stars or general relativity, although larger samples, the Crab pulsar, and the binary pulsar eventually did. It may well be the same for gravitational lenses; the major discoveries may have to await statistical samples and particularly simple or otherwise special objects.

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Soluble Lectins: A New Class of Extracellular Proteins

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Lectins are carbohydrate-binding proteins that were originally identified in plant extracts as agglutinins of erythrocytes (*1*). They have two critical properties: specificity for particular sugar residues; and bivalency or polyvalency (*2*). These properties make them useful for many purposes, including blood typing and the purification of glycoconjugates. For years they found wide applications as reagents, and little thought was given to the role they play in the plants from which they were derived.

Summary. Soluble lectins of cellular slime molds and vertebrates are present at extracellular sites in the developing or adult tissues that make them. Some lectins are concentrated around cell groups, as in extracellular matrix or elastic fibers. Others are at the interface between cells and the external environment, as in mucin or slime. Specific glycoproteins, proteoglycans, or polysaccharides that bind these endogenous lectins may also be present at these sites. Interactions between the lectins and glycoconjugates appear to play a role in shaping extracellular environments.

In the past decade, interest in the functions of lectins has increased considerably. This was stimulated by their isolation from many other organisms, including vertebrates and cellular slime molds—thereby attracting the attention of a wide range of biologists. In this article I summarize work on soluble lectins derived from these newer sources, especially as it relates to their biological roles in the tissues that make them. Studies of the functions of lectins in plants have been reviewed (*3*), and their relevance is considered briefly at the end of the article.

Soluble and Membrane Lectins

Lectins can be subdivided on the basis of whether or not they are integrated into membranes. The integral membrane lectins require detergents for solubilization, but the soluble ones do not. This subdivision probably reflects a fundamental difference in the general functions of these classes. In this view, the integral membrane lectins appear to have evolved to bind glycoconjugates to membranes, either at the cell surface or within vesicles. This results in the localization of the glycoconjugates at particular membrane sites or their transport to other cellular compartments (*4*). In contrast, soluble lectins, being excluded from membranes, cannot directly function in this way. Instead, they can move freely in the aqueous compartments within and between cells, interacting with both soluble and membrane-bound glycoconjugates.

The concept that integral membrane lectins function in endocytosis of glycoproteins or their intracellular translocation has experimental support (*4*). For example, the lectin of mammalian liver membranes that binds galactose is believed to function as a cell surface receptor for circulating asialoglycoproteins that contain terminal galactose residues. The asialoglycoprotein-lectin complex on the hepatocyte surface then undergoes endocytosis and is transported to other cellular compartments; this process may lead to degradation of the glycoprotein (*4*) or replacement of sialic acid (*5*). Several other vertebrate carbohydrate-binding proteins have been identified and these also appear to function in cellular translocation of glycoproteins (*4*). They bind other carbohydrate residues including mannose 6-phosphate, fucose, *N*-acetylglucosamine, and mannose. The functions of these integral

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