

Quasars

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Abstract.

I review recent results for quasars and discuss how they are related to activity in galaxies. Topics included are studies of quasar host galaxies with HST; searches for quasars in the Hubble Deep Field; evolution of the quasar luminosity function; news highlights from astro-ph; and current observational research problems and their relation to theoretical work.

1. Introduction

Our meeting occurs 35 years after the discovery of quasars, a discovery that transformed our concepts of active galactic nuclei (AGN), even though the connection between quasars and AGN was not clear at the time. We now consider quasars as the most luminous class of AGNs. Their great luminosity, which can be more than 1000 times that of an L^* galaxy, is part of their mystery on the one hand, while on the other hand it enables us to observe them at the greatest distances and earliest epochs at which they occur in the universe.

One of the great values of this symposium is that it brings together people from all fields of AGN research and provides us with an opportunity to take a fresh look at the state of the field and the key research problems.

In this talk I will cover some of the highlights of quasar history as they apply to our topic and review the main properties of quasars as we define them today. I will discuss recent results in quasar research, especially those that bear on the relation of quasars to activity in galaxies. I will also describe some current research problems and consider future opportunities for the field that will be provided by large telescopes and the large quasar surveys that are under way.

2. History

While the discovery of quasars in 1963 (Schmidt 1963) is well known¹, I would like to mention that it was preceded in 1958, forty years ago, by a key paper by Burbidge at the Paris Symposium. He pointed out that tremendous energy, 10^{60} ergs, resided in extragalactic radio sources. This was an unprecedented amount for the time, and the paper was influential in forcing people to think

¹The 1st Texas Symposium on Relativistic Astrophysics (Robinson, Schild, & Schucking 1965) still makes excellent reading about that feverish first year of work.

about non-stellar sources of energy in galaxies, that is, what we now call activity in galaxies.

To continue with the topic of milestone years, we can also note that the evolution of the quasar population was discovered by Schmidt in 1968, thirty years ago, a discovery that was an essential first step to showing that the characteristic time-scale for quasar activity is quite short in cosmological terms.

3. Definitions

Schmidt’s classic definition is that quasars are star-like objects of large redshift. More quantitatively, quasars are generally considered to have $z > 0.1$ and $M_B < -23$ ($H_0 = 50$) mag (see Schmidt and Green 1983). Traditionally, i.e. at resolutions of 1 – 2 arcsec, they were considered as being star-like, a description that is intertwined with the redshift and absolute magnitude limits just given. We now know that better spatial resolution often yields evidence of a host galaxy. Other key properties of quasars are that they have broad emission lines² in their spectra and that they can emit continuum radiation across the electromagnetic spectrum from γ -rays to radio waves, with ultraviolet and X-ray emission usually being very prominent. Also, quasars show variability on time scales of days to years.

How well can we explain all these properties? Although it is generally believed that the picture of an accretion disk surrounding a black hole is correct, agreement between current models and observations is distressingly poor in many cases.

Operationally, it is important to be aware of the effect of the apparent size and luminosity limit in the definition of quasars on modern surveys. For example, as the angular resolution of surveys improves to 1 arcsec or better and the depth of surveys increases either because of the use of larger aperture telescopes or longer exposures, the host galaxies of quasars will be increasingly visible. In such cases, strict imposition of the “star-like” criterion for quasars will exclude bona-fide AGNs.

Similarly, we now know that high-luminosity Seyfert galaxies can overlap in absolute luminosity with low-luminosity quasars, and analyses of surveys must allow for this. For example, deep surveys for quasars with good angular resolution will find both quasars and AGNs. It is important for the determination of the evolution of the entire AGN population that surveys consider what classes of objects they are including and perhaps rejecting.

4. Recent Results

4.1. Host Galaxies

The Hubble Space Telescope (HST) has provided critical new information on the nature of the host galaxies in which quasars reside and about the nature

²For this article, BL Lac objects will be considered as a separate class, although they are members of the AGN family.

of quasar environments. The excellent image quality of the repaired telescope gives the best combination of angular resolution and light gathering power yet applied to quasars. Here I report on two papers, which of course build on previous ground-based work.

Bahcall et al. (1997) presented results with the Wide-Field Camera of HST for 20 luminous quasars with $z < 0.3$. For the host galaxies, they found that 2 were as bright as the brightest cluster galaxies, 10 were like normal elliptical galaxies, 3 were normal spirals, 3 were complex, interacting systems, and in 2 cases there was faint nebulosity surrounding the quasar. For the radio-quiet quasars, 7 occurred in elliptical galaxies and 3 in spirals. For the 6 radio-loud quasars, 3 to 5 of them were in elliptical galaxies. On average, the host galaxies were 2.2 magnitudes brighter than normal field galaxies. In 8 cases, they detected companion galaxies within a projected distance of 10 kpc from the quasar nucleus. The interactions, presence of companions, and higher density of galaxies seen around quasars suggest that interactions are important to quasar activity.

Boyce et al. (1998) used HST in a complementary study of 14 low-redshift quasars. They find that 9 occur in elliptical galaxies (all 6 of the radio-loud quasars and 3 radio-quiet objects); 2 radio-quiet quasars are in disk galaxies, and the other 3, which are radio-quiet, ultraluminous IR objects, occur in violently interacting systems. The average luminosity of the quasar host galaxies is 0.8 magnitudes brighter than L^* , while the radio-loud objects are 0.7 magnitudes brighter than the radio-quiet ones.

It is evident, as Bahcall et al. point out, that the hosts and environments of quasars are complex, and that the previous ideas about radio-quiet quasars residing in spiral galaxies and radio-loud quasars in ellipticals may not hold up. However, it is perhaps more important to realize that the HST observations provide powerful support for the concept of quasars residing at the centers of galaxies and that galaxy interactions play an important role in quasar activity.

4.2. The Hubble Deep Field

The Hubble Deep Field (HDF) has given us unprecedented new views of distant galaxies. In combination with spectroscopic observations with the Keck Telescopes, studies of galaxies are now well advanced at $z > 3$, redshifts that were unattainable previously. Consequently, we now have the opportunity to study directly the relationship of galaxies and quasars at and beyond the redshift of peak quasar activity.

Recently Conti et al. (1998) have carried out a detailed search for compact quasars and AGNs in the HDF to $V_{606} = 27$ mag to study their presence and behavior at luminosities corresponding to AGNs in the nearby universe. Although the HDF contains more than 3000 galaxies, Conti et al. found an upper limit of 20 for the number of quasar candidates. Based on spectroscopic observations to date, the actual number may be much smaller, even close to 0. However, because of the great depth of the HDF exposures and the ~ 0.1 arcsec image quality, it is possible that any AGNs in the HDF are spatially resolved, and the next step is to develop sensitive techniques to detect AGN within faint, resolved galaxies in the HDF. A complication is that many of the distant galaxies being found by HST and Keck are undergoing intense star formation, which gives them

colors similar to those of many quasars. Jarvis and MacAlpine (1998) report identification of 12 resolved objects harboring candidate AGN. The crucial next step will be to confirm the nature of the candidates with follow-up spectroscopy, a very difficult task because of their faintness.

4.3. Evolution of the Luminosity Function

One of the most striking observed features of quasars is the evolution of their luminosity function. The space density of luminous quasars increases by a factor of ~ 1000 between the present epoch and redshift 2–3 and then falls steeply toward higher redshifts (Warren, Hewett, & Osmer 1994, WHO; Schmidt, Schneider, & Gunn 1995, SSG; Kennefick, Djorgovski, & de Carvalho 1995). A straightforward explanation of this behavior is that we are seeing back to the epoch of peak quasar activity, an epoch that presumably has to do with the formation of black holes at the centers of galaxies and the time of significant fueling of the quasar activity via the infall of material to the center.

However, a persistent question about the nature of the peak is whether it is affected significantly by dust absorption along the line of sight. If so, there could be an important population of quasars at high redshift that are hidden at optical/UV wavelengths, indicating that the epoch of peak activity was even earlier. There is no doubt that some quasars are highly reddened; the basic question is how many.

One way to answer this question is to use samples of radio-selected quasars with complete optical identifications. Dust is transparent to radio radiation, and so samples with complete optical identifications provide an excellent test, as long as the ratio of radio quasars to the total number of quasars does not change significantly with epoch.

Hook, Shaver, and McMahon (1998) have carried out just such a program and find that the evolution of quasars in their sample is remarkably similar to that found by WHO and SSG. This suggests that dust is not the cause of the apparent decline in activity at $z > 3$. Similarly, Benn et al. 1998 used IR observations in the K band of radio-selected quasars and found no evidence for a large population of reddened and dust-absorbed quasars. These results are in contrast to those of Masci (1998), who does claim evidence for a population of reddened objects.

The ultra-deep ROSAT survey of Hasinger et al. (Hasinger 1998) has yielded important new X-ray results. The good positional accuracies of the survey show that most of the sources are quasars/AGNs and narrow emission-line galaxies are only a small fraction, in contrast with some previous work. Their new determination of the X-ray luminosity function is not consistent with pure luminosity evolution but can be fit by pure density evolution from $z = 0$ to $z \approx 2$. Their results suggest that black holes should be common in massive galaxies at the present epoch, as discussed in more detail below.

5. The News

The astro-ph electronic preprint archive has had a large impact on our field by greatly increasing the accessibility of preprints and making them instantly available around the world. It also provides a convenient way of tracking the

latest developments. Here I mention a few highlights gleaned from postings to astro-ph in the last year and from other sources.

The Most Luminous. Irwin et al. (1998) reported the discovery of APM 0279 + 5255, a broad-absorption line quasar with $z = 3.87$ and $R = 15.2$ mag. The object is coincident with an IRAS FSC source, and the estimated luminosity is $\approx 5 \times 10^{15} L_{\odot}$, making it the intrinsically most luminous object known. There is evidence that the source is gravitationally lensed, which amplifies the true emitted luminosity.

The Most Distant. Weymann et al. (1998) find from Keck spectroscopy an emission line in the galaxy HDF4-473.0 that, if identified with $\text{Ly}\alpha$, yields a redshift of $z = 5.60$. The galaxy is in the Hubble Deep Field and is the most distant object with slit spectroscopy that has yet been identified. It is not a quasar or AGN, and the absence of quasars with $z > 4.9$, despite continuing surveys for them, is beginning to appear significant in view of the increasing number of confirmed and candidate galaxies with $z > 5$.

The Smallest. Kedziora-Chudczer et al. (1998) observed significant radio variability on timescales less than an hour in the radio quasar PKS 0405 – 385, which would make it the smallest extragalactic source observed. They attribute the variation to interstellar scintillation of a source with an angular size smaller than 5 microarcsec. The inferred brightness temperature is well above the inverse Compton limit. If interpreted as steady relativistic beaming, the Lorentz factor would be 1000.

The first FIRST gravitational lens. Schechter et al. (1998) found that the quasar FBQ 0951 + 2635, with $V = 16.9$ mag and $z = 1.24$, from the FIRST radio survey, is a gravitational lens with two images separated by 1.1 arcsec.

Update to the Verón-Cetty and Verón Catalog. Verón-Cetty and Verón released the 8th edition of their catalog during the year. It contains entries for 11,358 quasars, 357 BL Lac objects, and 3334 AGNs and is available electronically at <http://obshpz.obs-hp.fr/www/catalogues/veron2.8.html>. Such catalogs continue to be an vital resource for the community, especially as new surveys yield so many new quasars and AGNs. Also, the electronic availability of the catalogue makes it even more accessible and valuable than it was previously.

6. Some Current Research Problems

Here I call attention to some current research problems that need further work. Their eventual solution should improve our understanding of quasars and AGNs in important ways.

The Disagreement between Observations and Predictions for Accretion Disks. Koratkar (1997) points out that observations do not confirm most predictions of accretion disk models. For example, the Zheng et al. (1997) composite spectrum for ultraviolet wavelengths does not match predictions, and soft X-ray fluxes are observed to be too flat. Fewer Lyman edges are observed than predicted. Polarization is not seen either, which seems to rule out scattering as a way of smoothing the Lyman edges. An additional theoretical question is how the radiation from the accretion disk couples with that of the hot (X-ray) corona. It is important to resolve these issues if we are to have confidence in this basic part of our concept for quasars and AGNs.

What powers Ultra-luminous IRAS galaxies? Observations by Genzel et al. (1998) indicate that massive stars predominate in 70–80% of the cases, with AGNs dominating in the others. At least half of the systems probably have both an AGN and a circum-nuclear ring of starburst activity. They see no clear trend for the AGN component to dominate in the most compact and presumably most advanced mergers.

Do all galaxies have massive black holes? van der Marel (1997) notes that available data appear consistent with most galaxies having black holes, whose mass roughly correlates with the luminosity of the spheroid (cf. Magorrian et al. 1998). The black holes could have formed in or prior to a quasar phase and grown via mass accretion. Some of the implications of this work are discussed below under the theory section.

Is the broad Fe $K\alpha$ line produced directly near a black hole? How well do we understand the origin of X-ray emission in general? Observations of the broad Fe $K\alpha$ line in AGNs are widely interpreted as arising in the inner part of accretion disks around black holes and therefore providing both confirmation of the presence of black holes as well as direct information about conditions in the disks. However, Weaver and Yaqoob (1998) have raised questions about whether the emission in fact does occur so close to the centers of AGNs. More generally, intensive monitoring of NGC 7469 in X-rays and the ultraviolet by Nandra et al. (1998) provides strong constraints on quasar models. The data are not consistent with the UV emission being reprocessed by gas absorbing X-rays nor with the X-rays arising from Compton upscattering of the UV radiation.

These are just some examples of research problems in need of solution for us both to have confidence in our general picture of quasars and AGNs being powered by accretion onto massive black holes and to develop a quantitative understanding that explains the major observed features of these objects.

7. Theory

In addition to the above types of problems, considerable research is directed to basic questions such as, Do we understand how quasars form and evolve? Can we connect theories of galaxy and black hole formation with the observations of quasars at high redshift and the incidence of black holes in galaxies at low redshift? Here I mention briefly some recent theoretical work that demonstrates progress in our understanding of quasars and ties in with present and future observational work.

Haiman, Madau, and Loeb (1998) point out that the scarcity of quasars at $z > 3.5$ in the Hubble Deep Field implies that the formation of quasars in halos with circular velocities less than 50 km/s is suppressed (on the assumption that black holes form with constant efficiency in cold dark matter halos). They note that the Next Generation Space Telescope should be able to detect the epoch of formation of the earliest quasars.

Cavaliere and Vittorini (1998) note that the observed form for the evolution of the space density of quasars can be understood at early times when cosmology and the processes of structure formation provide material for accretion onto

central black holes as galaxies assemble. Quasars then turn off at later times because interaction with companions cause the accretion to diminish.

Haehnelt, Natarajan, and Rees (1998) show that the peak of quasar activity occurs at the same time as the first deep potential wells form. The Press-Schechter approach provides a way to estimate the space density of dark matter halos. But the space density of $z = 3$ quasars is less than 1% that of star-forming galaxies, which implies the quasar lifetime is much less than a Hubble time. For an assumed relation between quasar luminosity and timescale and the Eddington limit, it is possible to connect the observed quasar luminosity density with dark matter halos and the numbers of black holes in nearby galaxies. The apparently large number of local galaxies with black holes implies that accretion processes for quasars are inefficient in producing blue light.

8. Future Directions and Possibilities

The research problems and theoretical ideas described in this article are already open to observational study and testing with 8-10-m class telescopes and the Hubble Space Telescope, as we have discussed in the case of studies of quasar host galaxies, high-redshift galaxies, and black holes in galaxies. As the capabilities of the large ground-based telescopes improve (via infrared optimization and adaptive optics, for example), and when the Next Generation Space Telescope is completed, we will be able to study directly the relation of AGNs and galaxies over virtually the entire range of their evolutionary history. Similarly, the X-ray observatories AXAF and XMM will offer very significant new capabilities for the study of both the nature of quasars and AGNs and their evolution.

In the meantime, large-area, ground-based surveys such as the Sloan Digital Sky Survey³ and the 2dF⁴ survey will increase the number of known quasars by more than an order of magnitude. We may expect that the combination of the new samples, the new observatories, and continued theoretical advances will answer many of the questions raised here.

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³www.sdss.org

⁴msowww.anu.edu.au/~rsmith/QSO_Survey/qso_surv.html

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