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The Evolution of Quasars

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Abstract

This article reviews and discusses (1) the discovery and early work on the evolution of quasars and AGNs, (2) the different techniques used to find quasars and their suitability for evolutionary studies, (3) the current status of our knowledge of AGN evolution for $0 < z < 6$, (4) the new results and questions that deep radio and X-ray surveys are producing for the subject, (5) the relation of AGNs to the massive black holes being found in local galaxies and what they tell us about both galaxy and AGN evolution, and (6) current research problems and future directions in quasar and AGN evolution.

1.1 Introduction and Background

The subject of the evolution of the active galactic nucleus (AGN) population began in the late 1960s with Schmidt's (1968, 1970) discoveries that the space densities of both radio and optically selected quasars increased significantly with redshift. The effect was so strong that it was detectable in samples as small as 20 objects. He developed and applied the V/V_m test for analyzing the space distribution in his samples and showed that there was a strong evolution in the space density of quasars toward higher redshift, increasing by more than a factor of 100 from redshift 0 to 2. This was a striking and unexpected result that posed a question that is still crucial today—What causes the sharp decline since $z = 2$?

In this article I will review and discuss the following subjects:

- The techniques used to discover quasars and AGNs, their selection effects, and the surveys used to study the evolution of the AGN population.
- The general picture of evolution up to 1995, when the first well-defined, quantitative surveys of the evolution of high-redshift quasars were published.
- The current status of major optical surveys such as 2dF and SDSS.
- Radio and X-ray surveys and how they are critical to understanding AGN evolution.
- The relation of AGNs to their host galaxies and how studies of massive black holes in spheroids provide constraints on AGN evolution.
- Current research problems, such as measuring the quasar luminosity function at high redshift and faint magnitudes; relating observed to physical evolution; the framework for connecting observations, accretion processes, and the growth of black hole masses; and how to estimate black hole masses.

Before proceeding, let us define and discuss terms used in this article to aid the clarity of the presentation.

An AGN is one not powered by normal stellar processes, although active star formation may be occurring in the vicinity. The working hypothesis is that AGNs contain massive black holes and are powered by accretion processes. Their luminosities range from as low as $M_B = -9$ mag to as high as $M_B = -30$ mag ($L_X = 10^{38}$ to 10^{48} erg s^{-1}). Quasars are the high-luminosity ($M_B < -23$ mag, $L_X > 10^{44}$ erg s^{-1}) members of the AGN family.

Traditionally, evolution of AGNs or quasars has meant the evolution with redshift of their luminosity function or space density (which is the integral of the luminosity function over some range of luminosities). However, evolution can also refer to changes with redshift of the spectral energy distribution (SED) or the emission-line spectra of AGNs. In general, *observed* evolution will refer to changes with redshift of any observed property of AGNs.

Ultimately, we wish to map and understand the *physical* evolution of AGNs, by which we mean how their central black holes form and grow with cosmic epoch and how their accretion processes and rates, which determine the luminosities and SEDs we observe from AGNs, evolve with cosmic epoch. The discovery of the ubiquity of black holes in the spheroids of nearby galaxies makes us realize that the physical evolution of AGNs is closely connected with and is an important part of the larger subject of how galaxies in general form and evolve. It appears that virtually every spheroidal system went through an AGN phase at some time in its history—thus the subject of our meeting: "The Coevolution of Black Holes and Galaxies."

However, the persistent question of how many AGNs are hidden because of weak emission lines, obscuration by dust, or absorption in X-rays has continued to impede progress in the mapping of the observational evolution of AGNs and must be addressed in any attempt to determine the properties of the overall AGN population. Fortunately, the advent of powerful new space observatories such as *Chandra* and *XMM-Newton*, in conjunction with sensitive radio and infrared surveys, provides new tools for attacking this problem, as will be addressed below.

At the same time, the formulation and application of the appropriate observational definitions of AGNs continue to be critical issues in current research, especially for low-luminosity objects, which can be hard to find within the glare of their host galaxy or to separate from normal stars. For example, the work of Ho (2003) suggests that some AGNs may have X-ray luminosities down to 10^{36} erg s^{-1}, or less than stellar X-ray sources.

If we are really to understand the global population of AGNs and their relation to galaxies, these problems must be solved. This will be one of the themes to be developed in this article.

1.2 Observational Techniques, Selection Effects, and Surveys

The general principle for discovering AGNs is to make use of one or more of the ways in which they are not like stars or galaxies, for example, how they differ in the SEDs or emission-line spectra. The pointlike, i.e., spatially unresolved, nature of the nuclei is another distinguishing factor. It is also possible to make use of their great distances and correspondingly undetectable proper motions in quasar and AGN searches or their variability in brightness. In this article we will concentrate on techniques that make use of their SEDs and spectral-line properties.

The SEDs of AGNs are remarkable for their broad extent in frequency, from radio to γ-rays, which is much greater than for normal, thermal sources of astronomical radiation. The UV/optical emission-line spectra stand out for the strength and breadth of the principal emission lines and for the wide range of ionization. Typical line widths of permitted lines are 5000 km s^{-1} or more. The strongest individual lines are those of hydrogen (Lyα, Hα, and Hβ), C IV, C III], Mg II, and N V, while broad emission complexes of Fe II are visible. In addition, forbidden lines of [O I], [O II], [O III], and [S II] are prominent.

Some of the observable properties of AGNs provide diagnostic probes of the physical nature of the central engine. For example, the X-ray emission originates in regions as close as a few Schwarzschild radii of the central black hole and yields information about the inner part of the accretion disk and coronal region. The broad UV/optical emission lines are produced within a few light days of the central engine. One main goal of AGN research is to combine multiwavelength and spectral observations of AGNs with theoretical models of the accretion processes so that physical properties such as accretion rates and efficiencies can be inferred from observable data. When success is achieved in this subject, it will yield a significant advance in our understanding of AGN evolution.

1.2.1 Techniques for Finding Quasars and AGNs

1.2.1.1 Quasars

Historically, quasars were first discovered (Hazard, Mackey, & Shimmins 1963; Schmidt 1963) via the optical identification of radio sources, a technique that was both effective and efficient because normal stars and galaxies are much weaker sources of radio emission. It was soon realized (Sandage 1965) that the bulk of the quasar population was radio quiet and could be identified through the excess UV (UVX) radiation that quasars demonstrated relative to normal stars*. We now know that the UVX technique is effective for redshifts up to about 2.2, the point at which Lyα emission shifts into the observed *B* band and quasars begin to lose their characteristic UV excess. We also know now that only about 10% of quasars and AGNs in the early samples were strong radio emitters, or radio-loud objects.

At higher redshifts, different techniques must be used to find quasars. The problem becomes difficult for two reasons: (1) at redshifts around 3, the optical/UV SEDs of quasars are hard to distinguish from stars, and (2) the space density of quasars at $z > 3$ declines rapidly with increasing redshift.

The slitless-spectrum technique pioneered by Smith (1975) and developed by Osmer & Smith (1976) provided a color-independent method of finding high-redshift quasars through the direct detection of their strong, broad emission lines, in particular Lyα, on low-dispersion objective-prism photographs. The technique was then applied to large telescopes through the use of a transmission grating/prism combination (grism) as the dispersing device (Hoag 1976). However, it was also realized that the slitless-spectrum technique was subject to an important selection effect in that it favored the detection of quasars with strong emission lines†.

Schmidt, Schneider, & Gunn (1986) made an important advance on this problem by using a digital detector with a grism at the Hale 5-m telescope and by developing and applying a numerical selection algorithm for identifying emission-line objects whose properties and efficiencies could be quantified. The effectiveness of their approach is well demonstrated in

* For the record, most stars are UV faint and quasars have relatively flat optical/UV SEDs in νf_ν space.

† Of course, all observational techniques for discovering quasars and AGNs are subject to selection effects. This has been a long-standing problem in the determination of their luminosity function and its evolution. Nonetheless, it appears that the slitless-spectrum technique indeed discovers the bulk of the high-z population, although it obviously misses objects with weak or no emission lines.

Figure 2 of their paper, which shows the grism spectra for a variety of high-redshift quasars from their survey.

The advent of rapid plate-scanning machines such as COSMOS and APM enabled the extension to higher redshift of color-based techniques for discovering quasars. Warren et al. (1987) found the first quasar with $z = 4$ in this way. The machines and multi-color techniques made it possible to use more sophisticated combinations of colors to separate quasars from stars and to provide quantitative estimates of the selection efficiency as a function of redshift and apparent magnitude, which were crucial for determining the luminosity function. Subsequently, the Sloan Digital Sky Survey (SDSS; York et al. 2000) combined the multi-color technique with a dedicated survey telescope and the largest digital camera built until that time to open a new frontier in extragalactic research by undertaking a digital survey of 10,000 deg^2 in five filters; the initial results are described in more detail below.

1.2.1.2 AGNs

We now know that the discovery of AGNs preceded quasars by 20 years (Seyfert 1943), although the connection and understanding was not achieved until the mid-1970s. Seyfert's classic paper described the properties of nearby galaxies with unusually bright nuclei, which also had unusual emission-line spectra, in particular, broad lines and a wide range of ionization. Seyfert galaxies and related AGNs such as LINERs (low-ionization nuclear emission-line regions), which are less luminous than $M_B = -23$ mag, constitute the bulk of the AGN population. Their most prominent members can be discovered through imaging and spectroscopic surveys following in the footsteps of Seyfert. However, the discovery of lower-luminosity, more elusive members of the class requires much more care, as the work of Ho, Filippenko, & Sargent (1995) has shown. They examined carefully *all* galaxies within a magnitude-limited survey with high- quality, narrow-slit spectra for evidence of an active nucleus.

Most recently, Heckman (2004) and Hao & Strauss (2004) have demonstrated that careful application of stellar population synthesis modeling to SDSS galaxy spectra can pull out otherwise unrecognizable emission-line and AGN signatures through the careful subtraction of the young stellar and nebular emission population. Their work indicates that the presence of weak AGN activity is much more common than originally thought and is found in the majority of early- and middle-type galaxies.

1.2.1.3 Radio and X-Ray Techniques

The discovery and identification of quasars and AGNs by radio and X-ray techniques is perhaps the most straightforward of all, because normal stars and galaxies are weak emitters in these wavelengths. One requires sufficient sensitivity to compact sources and positional accuracies of $\sim 1''$ on the sky. Objects in radio and/or X-ray catalogs are then matched to optical catalogs for identifications and follow-up optical spectra with a large telescope are used to confirm the identification and establish the redshift of the object. Radio and hard X-ray sources offer the important advantage that they are not affected by dust obscuration that may occur along the line of sight to the AGN. If spectral information is available in the 1 keV range, then estimates of the column density of any absorbing gas along the line of sight may be made.

Until recently, radio surveys were hampered by the fact that, as mentioned previously, only about 10% of AGNs are radio loud and thus radio surveys included only a small fraction of the total population. However, with the advent of deep, wide-area surveys such as FIRST (Becker, White, & Helfand 1995), important new opportunities have arisen. FIRST, which reaches to milli-Jansky flux limits, is sufficiently sensitive to detect *radio-quiet* quasars. When used in conjunction with the multi-color imaging data of the SDSS, it has enabled the discovery of new classes of AGNs (e.g., reddened broad absorption-line quasars that are radio sources) and added a new perspective on the issue of dust obscuration.

The combination of FIRST and SDSS data overcomes another problem with earlier radio surveys, namely, the difficulty of achieving effective redshift preselection for candidate objects. The difficulty was that follow-up spectroscopy of a large number of candidates had to be carried out to find high-redshift or rare types of quasars and AGNs. However, the multicolor SDSS data now can be used to pre-sort candidate objects into the desired groups for follow-up work.

X-ray data have been important to the study of quasars and AGNs since their first detections in X-rays because it was realized that the emission likely originated from very close to the central black hole. Indeed, it can be argued that X-ray emission is the defining characteristic of AGNs (e.g., Elvis et al. 1978). However, the point was somewhat moot at the time because of the lack of sensitivity of the original X-ray observatories. Now, following the work with *ROSAT* and the initial results from *Chandra* and *XMM-Newton*, the tables are turned—the deepest X-ray surveys are picking up objects not previously noted in optical surveys.

1.2.1.4 Summary

Discovery and survey techniques for quasars and AGNs at X-ray, UV/optical, and radio wavelengths are now sufficiently well developed, quantified, and sensitive that we have the main tools in hand to settle many of the most fundamental observational questions about the evolution of the AGN population. The combinations of multiwavelength data that are now possible add even more opportunities for research on the nature of AGNs.

1.3 Evolution of the AGN Population

1.3.1 Results through 1995

Schmidt's discovery of the evolution of the quasar luminosity function immediately stimulated work on the nature of the evolution. While powerful for showing the existence of evolution, the V/V_m test by itself was not capable of delineating the nature of the evolution. Furthermore, the available quasar samples were too small to permit analyses in much detail. Schmidt explored different forms of density evolution, i.e., evolution of the number density with cosmic epoch. He found that both a power-law evolution of the form $(1+z)^k$ and an exponential function of look-back time could fit the data up to redshift 2. Mathez (1976, 1978), building on the work of Lynds & Petrosian (1972), demonstrated that luminosity evolution, in which the characteristic luminosity of quasars increased with redshift also provided a satisfactory fit to the data. Schmidt & Green (1983) presented results from the 92 quasars in the Palomar Bright Quasar Survey that showed the increase of space density with redshift to depend on the luminosity of the objects. This indicated that a simple parameterization of either pure density or pure luminosity evolution did not fit the data well.

Subsequently, the work of Boyle, Shanks, & Peterson (1988, hereafter BSP), using the UVX technique, marked a significant advance in sample size and limiting magnitude. They compiled a sample of 420 quasars to $B < 20.9$ mag from UK Schmidt plates scanned with COSMOS. They found that a two-power law luminosity function and luminosity evolution adequately describe the data for objects with $M_B < -23$ mag and $z < 2.2$, a result that has been widely used and is consistent with recent 2dF results, as described below.

Thus, the situation by the late 1980s was that either the space density of quasars increased by more than a factor of 100 between redshift 0 and 2 (Schmidt & Green 1983), or their characteristic luminosity increased by a factor of 30 (BSP).

It was also understood that the density and luminosity evolution pictures led to significantly different estimates of the lifetimes of quasars, about 10^7 years in the density evolution picture and 10^9 years or more in the luminosity evolution picture. Another consequence was that most galaxies would pass through a quasar phase in the density evolution model; for luminosity evolution, only a few percent of galaxies would be active.

A different and also important question was raised early on in studies of quasar evolution: What happened at high redshift, $z > 2$? The redshift histograms of quasar catalogs showed a marked decline in numbers at $z > 2$ (e.g., Hewitt & Burbidge 1980), with the implication that the evolution also declined. However, it was also realized that the traditional UVX method was not suitable for finding high-redshift quasars, and the lack of suitably defined samples blocked progress. As mentioned above, the slitless-spectrum technique provided an efficient means of discovering high-redshift quasars, and Osmer (1982) showed from a differential study with the CTIO 4-m telescope and grism that there was strong evidence for a decline in the space density of quasars at $z > 3$. Nonetheless, he could only provide an upper limit on the decline because no quasars with $z > 3$ were found in his survey, and it was clear that more work was needed. Also, it was pointed out by Heisler & Ostriker (1988) that dust absorption by intervening galaxies along the line of sight could produce a decline in the observed space density determined from flux-limited samples.

Significant advances occurred in the 1990s, when the first large, digital surveys for high-redshift quasars were carried out. Warren, Hewett, & Osmer (1991a,b, 1994, hereafter WHO) made use of APM scans of UK Schmidt plates in six colors, u, b_j, v, or, r, i to cover an effective area of 43 deg^2. Their sample contained 86 objects with $16 < m_{or} < 20$ mag and $2.2 < z < 4.5$. They developed a numerical modeling technique to determine the selection probabilities for their objects as a function of redshift and magnitude, allowing for different spectral slopes and emission-line strengths. They used the selection probabilities to make two different estimates of the quasar luminosity function and its evolution. They found strong evidence for a decline in the space density beyond $z = 3.3$ by a factor of 6 for the interval $3.5 \leq z < 4.5$ for luminous quasars with $M_C < -25.6$ mag*.

Schmidt, Schneider, & Gunn (1995, hereafter SSG, and references therein) used the Palomar Transit Grism Survey (Schneider, Schmidt, & Gunn 1994) to establish a sample of 90 objects with Lyα emission and redshifts $2.75 < z < 4.75$ to $AB_{1450} < 21.7$ mag in an area of 61.5 deg^2. Their digital survey used CCD detectors, and they determined the completeness and selection effects for their sample based on the line fluxes and signal-to-noise ratio of the data. Their sample contained 8 objects with $z > 4$, and they found a decline in the space density of a factor of 2.7 per unit redshift for quasars with $M_B < -26$ mag and $z > 2.7$. This result was very important because it used a survey technique different from WHO and had many more quasars with $z > 4$.

* M_C is the absolute magnitude on the AB system for the continuum level at Lyα (1216Å).

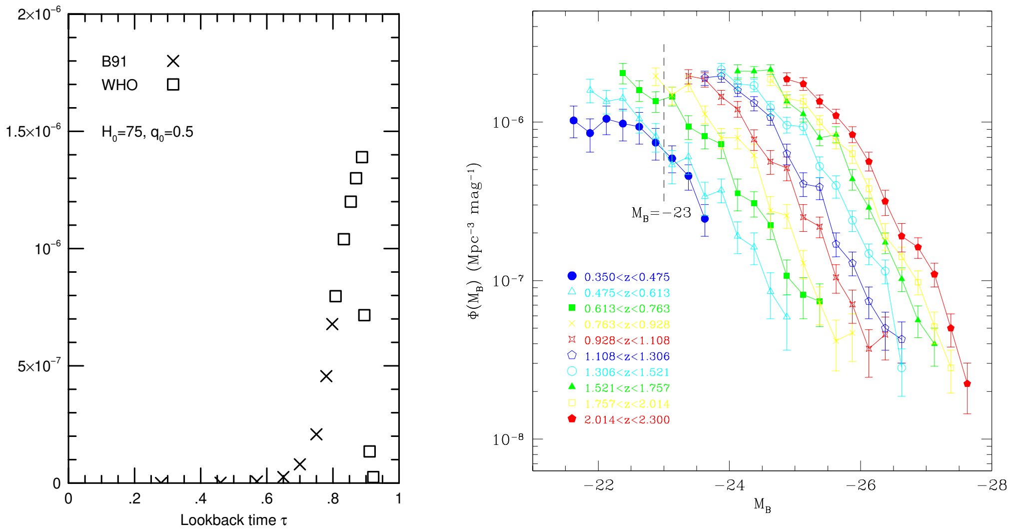

Fig. 1.1. *Left:* A linear plot of the space density of luminous quasars versus look-back time for the BSP and WHO samples. *Right:* The observed luminosity functions for the quasars with $0.35 < z < 2.3$ in the 2dF sample compiled by Boyle et al. (2000).

Kennefick, Djorgovski, & de Carvalho (1995) made use of three colors, J, F, N, in the second Palomar Sky Survey in a program covering 681 deg^2 in the magnitude range $16.5 < r < 19.6$. They had 10 quasars with $z > 4$ in their sample and found a decline in space density of a factor of 7 at $z = 4.35$ relative to $z = 2.0$.

Taken together, the three surveys agreed well within their respective estimated errors and provided convincing evidence for a steep decline at $z > 3$ in the observed space density of luminous, optically selected quasars. When the results are combined with those of BSP for lower redshifts and plotted on linear scales of space density versus look-back time (Fig. 1.1, *left*), the behavior is dramatic and indicates a remarkable spike of quasar activity when the Universe was 15%–20% of its current age.

At the same time, a number of important questions remained about the nature of the evolution of the quasar luminosity function: (1) At what redshift does the peak of the space density occur? This is a result of the optical SEDs of $z = 3$ quasars being similar to those of stars. (2) How do lower-luminosity quasars and AGNs, which constitute the bulk of the population, evolve? This requires deeper surveys. (3) What is the form of the evolution and its possible dependence on redshift? Hewett, Chaffee, & Foltz (1993) showed from a study of the 1049 quasars and AGNs from the Large Bright Quasar Survey, which cover $0.2 < z < 3$ and $16.5 < m_{B_J} < 18.85$, that the data are not fit well by a pure luminosity evolution model with a two-power law luminosity function. They found that the slope of the luminosity function became steeper at higher redshifts, the rate of evolution was slower for $0.2 < z < 2$ than the Boyle et al. results, and the evolution continued, more slowly, until $z \approx 3$. Thus, more work needs to be done.

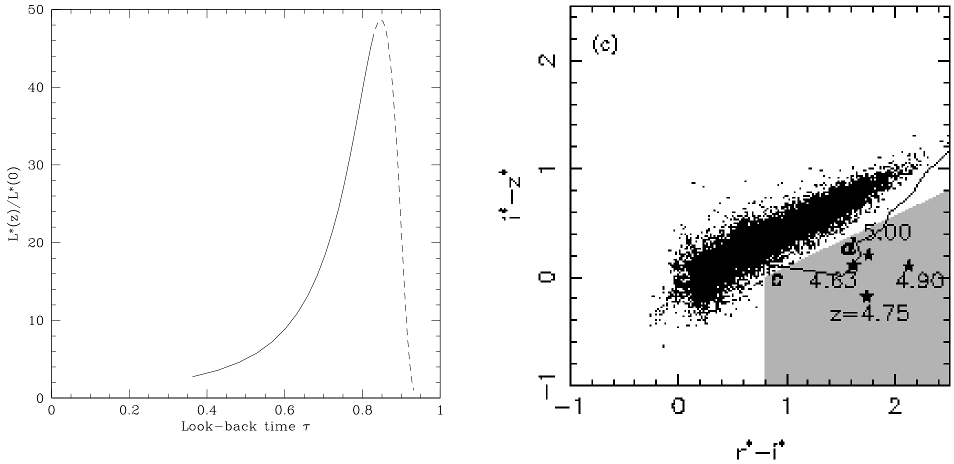

Fig. 1.2. *Left:* A linear plot of the characteristic luminosity of quasars from the 2dF (Boyle et al. 2000) and SSG samples versus look-back time, for the luminosity evolution model. *Right:* A $i^* - z^*$ versus $r^* - i^*$ plot of SDSS data, showing the stellar locus (black area and points) and how quasars with $4.6 < z < 5.0$ separate from the stellar locus because of the presence of Lyα emission in the i^* band and of Lyα forest absorption in the r^* band (Fan et al. 1999).

1.3.2 Recent Large Optical Surveys

The above-mentioned questions on the evolution of quasars provided a significant part of the motivation for two surveys significantly larger than anything previously attempted, the 2dF survey (Boyle et al. 2000, and references therein) and the SDSS (York et al. 2000). The goal of the 2dF was to cover 750 deg^2 of sky to $B < 21$ mag and find $> 25,000$ quasars with $z < 2.3$ via the UVX technique. The SDSS objective was to survey 10,000 deg^2 of sky in five colors, $u'g'r'i'z'$, to find 100,000 quasars covering all redshifts up to 5.8.

Boyle et al. (2000) have estimated the luminosity function from the first 6684 quasars in the 2dF quasar survey. The survey was based on u, b_J, r UK Schmidt plates and is primarily a UVX technique. It was estimated to be 90% complete for $z < 2$. Their final sample included 5057 objects from 196 deg^2 of sky with $M_B < -23$ mag, $18.25 < b_J < 20.85$, $0.35 < z < 2.3$. They combined their sample with 867 objects from the LBQS (Hewett, Foltz, & Chaffee 1995) and fitted a two-power law form to the luminosity function data. The data are shown in Figure 1.1 (*right*). They found that a polynomial evolution of $L^*_{B(z)}$ fits the data well (Fig. 1.2, *left*). Thus, their main conclusion is that for 2dF+LBQS, $-26 < M_B < -23$ mag ($q_0 = 0.5$) and $0.35 < z < 2.3$, pure luminosity evolution works fine, with the characteristic luminosity of quasars increasing by a factor of 40 at the peak of activity. However, the EQS (Edinburgh Quasar Survey, Miller et al., unpublished) and HEQS (Hamburg/ESO Quasar Survey, Köhler et al. 1997) do not fit as well, particularly for $z < 0.5$, where the LBQS has few or no data.

The SDSS opened an important window for the search for high-redshift quasars through its large areal coverage of the sky and its use of the z^* filter with $\lambda_{\rm eff} \approx 9100$Å, which extended the discovery space in redshift to $z = 5$ and beyond. Figure 1.2 (*right*) (Fan et al.

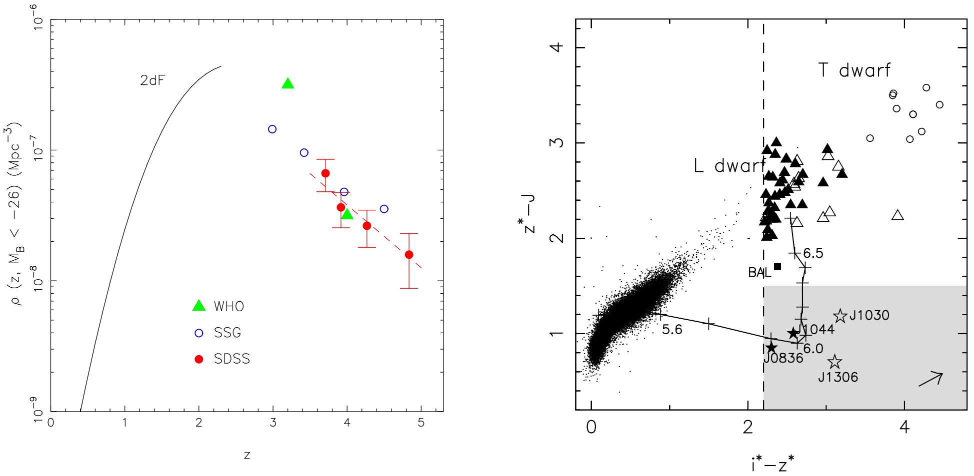

Fig. 1.3. *Left:* The space density of quasars with $M_B < -26$ mag as a function of redshift for the 2dF, SDSS, SSG, and WHO surveys (Fan et al. 2001b). *Right:* The $z^* - J$ versus $i^* - z^*$ diagram for the SDSS, showing how the infrared J band enables the separation of $z > 5.8$ quasars from the numerous L and T dwarfs (Fan et al. 2001c).

1999) illustrates how the r^*, i^*, z^* filters were used to discover the first quasars with $z \approx 5$ by their clear separation from the stellar locus.

Fan et al. (2001a,b) then used the technique to compile a well-defined, color-selected sample of 39 quasars with $3.6 < z < 5.0$ and $i^* \leq 20$ mag in 182 deg^2 of sky. They estimated the luminosity function for objects with $27.5 < M_{1450} < -25.5$ and its evolution with redshift. Their results, which are shown in Figure 1.3 (*left*) agree within the errors at $z \approx 4$ with the previous results of WHO, SSG, and KDC and give a value of the decline in space density of a factor of 3 per unit redshift for $z > 3.6$. They find a flatter slope for the luminosity function at $z \approx 4$ relative to earlier surveys for $z < 3$. These results confirm that pure luminosity evolution does not match the data between redshifts 2 and 5.

Then, Fan et al. (2001c) extended their work to discover four quasars with $z > 5.8$ by using observation in the infrared J band to help eliminate nearby and numerous L and T dwarf stars (Fig. 1.3, *right*). They showed that the space density at $z = 6$ is about a factor of 2 below that at $z = 5$ and follows the decline with redshift just described. These objects provide the strongest evidence yet for a detection of the Gunn-Peterson absorption and thus evidence for reionization at redshifts in the vicinity of $z \approx 6$*.

To summarize, the 2dF and SDSS results now cover the range $0.3 < z < 6.3$ for high-luminosity, optically selected quasars and reach close to the epoch of reionization. They provide by far the best data on the evolution of such quasars that exist to date.

1.3.3 Spectral Evolution

We should also comment on the spectral properties of high-redshift quasars, which look surprisingly like their low-redshift counterparts. The emission-line spectra of the first

* Note added in proof. Fan et al. (2003) announced the discovery of three additional quasars with $z > 6$.

quasars discovered at $z \approx 5$ (e.g., Schneider, Schmidt, & Gunn 1991; Fan et al. 1999) show C, N, O, and Si lines in the strengths normally seen at low redshifts. The Dietrich et al. (2002) compilation of spectra covering $0.5 < z < 5$ shows remarkably little evolution with redshift. While it is dangerous to jump to conclusions about abundances based on the appearance of strong emission lines, their lack of evolution is consistent with more detailed analyses. Put another way, we have no evidence for chemical evolution in quasar spectra, except that, if anything, some abundances were *higher* at high redshifts (Hamann & Ferland 1999).

1.3.4 Evolution of Radio Sources

At radio wavelengths, Hook, Shaver, & McMahon (1998), building on the work of Shaver et al. (1996), have carried out an important survey that bears on the question of possible obscuration by dust at high redshifts. Their sample contains 442 radio sources with $S_{2.7\mathrm{GHz}} \geq 0.25$ Jy and stellar identifications. The highest redshift object has $z = 4.46$. For objects with radio power $P_{\mathrm{lim}} > 7.2 \times 10^{26}$ W Hz^{-1} sr^{-1}, they find an evolution of the space density very similar to WHO, SSG, and the SDSS. This is strong evidence against dust reddening being the main cause of the decline at high redshifts.

At the same time, Webster et al. (1995) and Gregg et al. (2002) have argued that the finding of significant numbers of radio-selected quasars with very red values of $B-K$ in the Parkes and FIRST surveys indicates that up to 80% of the population is being missed in traditional optical surveys because of dust obscuration. This interpretation has been challenged by Benn et al. (1998) and Whiting, Webster, & Francis (2001) on the grounds that the brightness in K can arise from the emission of the host galaxy and/or synchrotron radiation, not from obscuration in the B band by dust. Until this issue can be resolved, the question of dust-obscured quasars remains important to our understanding of quasar evolution, as indicated by the new X-ray results described below. The finding of reddened quasars in the 2MASS survey (Marble et al. 2003, and references therein) is also contributing important information on this subject.

1.4 Estimating Black Hole Masses

Until this point we have discussed the *observed* aspects of the evolution of quasars and AGNs, primarily the evolution of their luminosity functions. Now let us begin to consider their *physical* evolution, for which estimates of the masses of the central black holes are crucial. Such estimates will enable us to map the growth of the black holes with cosmic epoch.

In this meeting we have heard about three ways to estimate black hole masses: (1) from their gravitational influence on the stellar velocity distributions or gas kinematics in the centers of galaxies, (2) reverberation mapping of the broad-line emission region (Barth 2004), and (3) the use of emission-line widths and continuum luminosities (e.g., C IV, Vestergaard 2002, 2004; Mg II, McClure & Jarvis 2004). The first two provide the underpinnings for the mass estimates but are limited to nearby galaxies and AGNs. The third method, while indirect and subject to more uncertainties, has great potential value because it provides the only practical way we have at the moment of estimating the masses of quasars and AGNs at high redshift.

Vestergaard & Osmer (in preparation) are using methods 2 and 3 to make estimates of the mass functions of quasar samples at low (the BQS, Schmidt & Green 1983) and high

(SDSS, Fan et al. 2001a) redshift. Their preliminary results indicate that the SDSS quasars have already achieved masses of $> 10^9 M_\odot$ at $z > 3.6$, and their cumulative mass density is more than a order of magnitude above the BQS sample. This indicates that luminous quasars at high redshift built up their masses early (see also Vestergaard 2004). The BQS cumulative mass density, on the other hand, is an indicator of how the luminous activity has declined rapidly by the present time, when luminous quasars are quite rare. Interestingly, the SDSS cumulative mass densities appear to fit on the extension of the results from the Padovani, Burg, & Edelson (1990) sample of Seyfert galaxies at low redshift. This is consistent with the idea that both the low-redshift Seyferts and low-luminosity AGNs and the high-redshift SDSS quasars have achieved a substantial fraction of their final black hole mass growth.

1.5 Theoretical Considerations: How the Masses Grow

All the recent observational data on quasars and AGNs, in combination with theoretical studies of their evolution and the accretion processes that produce both their luminosity and growth in mass, are now enabling new global studies of their history (e.g., Yu & Tremaine 2002; Yu 2004; Steed, Weinberg, & Miralda-Escudé, in preparation). The goal is to determine how an initial black hole mass function evolves into the one observed today in the local Universe by considering the continuity equation and how the the masses grow with accretion processes. The simple equation $L = \epsilon(\dot{m}/\dot{m}_{\rm Edd})Mc^2$, where L is the luminosity produced by an accretion rate $\dot{m}$ in Eddington units with efficiency ϵ for a black hole of mass M, tells us that if we could observationally determine L and ϵ along with black hole masses, for example, we would have enough information to model the evolution of the black holes in galaxies. Put another way, the general goal is to combine the black hole mass function, the time history of accretion, and the distribution of accretion rates and efficiencies to see if we can match the observed luminosity and mass functions for AGNs and black holes. One immediate problem at present is that we do not have a way of separately estimating ϵ and $\dot{m}/\dot{m}_{\rm Edd}$; typically people assume that ϵ is 0.1 or some range of values depending on the accretion models they adopt. Another problem is accounting properly for the number of obscured sources in flux-limited samples.

Nonetheless, there are enough existing data to permit interesting progress on the problem. For example, the combination of the black hole mass function for local galaxies and the X-ray background provide integral constraints that must be satisfied by any model. The mass function represents the end point of the accretion processes, while the X-ray background provides a measure of the integrated luminosity produced by accretion over the history of the Universe. The improved optical data on the quasar luminosity functions provide additional constraints on how and when this all occurred, because they map out the evolution of the emitted light with cosmic time. At the same time, the deep X-ray and radio surveys and related optical observations provide crucial information on the contribution of obscured sources to the accretion history of the Universe.

Yu & Tremaine (2002) find that the quasar luminosity functions and local black hole mass functions are consistent if $\epsilon \approx 0.1$ and the black hole mass growth occurred during the optically bright phase. The lifetime of luminous quasars would be of order 10^8 years. At the same time, there remain important questions about the accretion efficiency of lower luminosity quasars and AGNs and its dependence on accretion rate, for example.

1.6 Current Research Programs

1.6.1 Optical/Infrared Surveys

Building on the success of 2dF and SDSS in delineating the evolution of optically selected quasars at high luminosity, a next logical and important observational step is to map the evolution of lower luminosity objects. They constitute the bulk of the AGN population, and they are also crucial for understanding the nature of the extragalactic ionizing background radiation. At high redshift, there is already evidence that the numbers of quasars are too few to account for the observed level of ionization of the intergalactic medium (McDonald & Miralda-Escudé 2001; Schirber & Bullock 2003).

On the observational front, the slope of the luminosity function of high-redshift quasars is quite uncertain. Although Fan et al. (2001b) have made estimates, and the upper limits on the number of AGNs in the HDF also sets constraints (e.g., Conti et al. 1999), direct observations are needed, because it is the slope that determines the number of faint AGNs.

Among the current surveys for fainter quasars at high redshift are the BTC40 (Monier et al. 2002), COMBO-17 (Wolf et al. 2001), and the NOAO DEEP survey (Januzzi & Dey 1999). All are multi-color imaging surveys. In addition, Steidel et al. (2002) are investigating the AGN population found in a deep spectroscopic survey of Lyman-break galaxies. The main properties of these surveys are:

(1) BTC40 covered 40 deg^2 in B, V, I and 36 deg^2 in z and was designed to find quasars with $4.8 < z < 6$. It reached 3σ limiting magnitudes of $V = 24.5$, $I = 22.9$, and $z = 22.9$. To date it has yielded two quasars with redshifts of 4.6 and 4.8 and produced candidates down to $I = 22$ for future spectroscopy on 8–10 m telescopes.

(2) COMBO-17 uses 17 filters covering the $0.37 - 2.2\mu$ wavelength range to achieve in effect low-resolution spectroscopy for a 1 deg^2 area down to $R = 26$ mag. This survey, which will include 50,000 galaxies as well as quasars and AGNs, is very ambitious and promises to yield very significant results when completed.

(3) The NOAO DEEP survey is covering 18 deg^2 of sky in B_W, R, I, J, H, K to optical magnitudes of 26 and near-infrared magnitudes of 21. Because of its broad wavelength coverage and faint limiting magnitudes, it will provide very important data on the evolution of AGNs.

(4) The Steidel et al. survey complements the multi-color ones in that it investigates the spectroscopic properties of galaxies at $z \approx 3$ down to $R_{AB} \approx 25.5$ mag. It has found that about 3% of the galaxies are AGNs, many of which would not have been detected in deep X-ray surveys, and thus is sampling a part of parameter space not covered to date in other work.

An additional value of all these surveys will be to combine their results with those of the deep radio and X-ray surveys mentioned above. This will help define better the luminosity functions and statistics of quasars, AGNs of different types, and normal galaxies and thereby help improve our knowledge of the evolution of all these objects.

1.6.2 Evolution of X-ray Sources

The *Chandra* and *XMM-Newton* observatories are enabling X-ray surveys with sensitivity limits 2 orders of magnitude fainter than was previously possible because of their large collecting areas and exposure times of a million seconds. In the *Chandra* Deep Field South (Rosati et al. 2002), Figure 1.4 shows that the surface density of sources is greater than 3000 deg^{-2}. Thus, for the first time, the surface density of the deepest X-ray selected AGNs exceeds the values of a few hundred deg^{-2} that were achieved in early deep optical

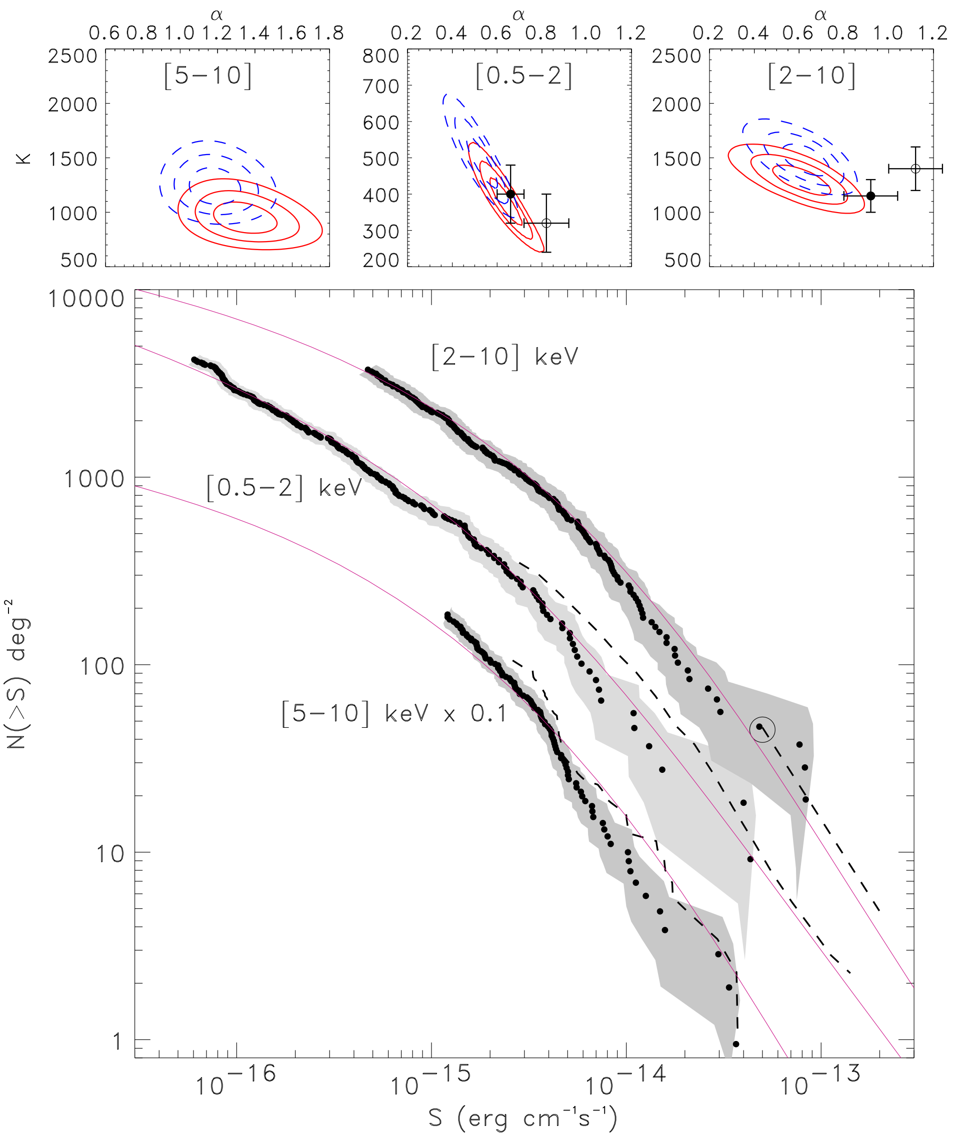

Fig. 1.4. The log N–log S data for the *Chandra* Deep Field South survey for three different energy bands. The upper boxes show the fits for the normalization constant, κ, and slope, α, of the faint end of the data (Rosati et al. 2002).

surveys. However, it is also now possible to carry out optical imaging and spectroscopic observations for sources that are 2 orders of magnitude fainter than the nominal limit of SDSS, for example. These capabilities have led both to important discoveries and to the opening up of important areas of research.

For example, the deep source counts show that most of the X-ray background (XRB) can be resolved and accounted for by faint discrete sources. However, to match the SED of

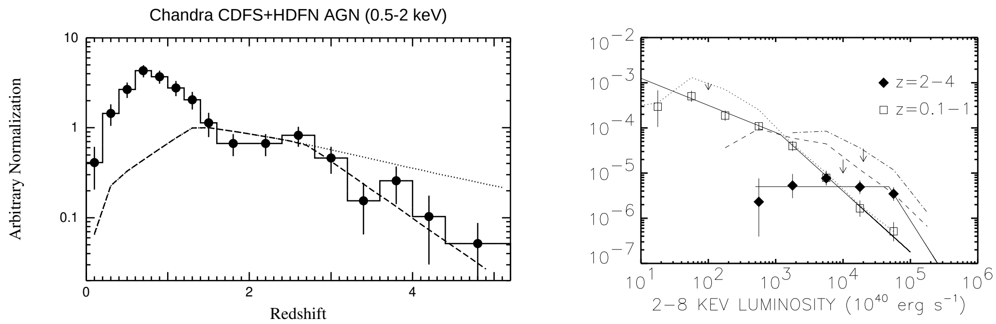

Fig. 1.5. *Left:* The redshift distribution for 243 AGNs in the *Chandra* Deep Field South and Hubble Deep Field North surveys, from Hasinger (2004), compared to population synthesis models by Gilli et al. (2001), where the dashed line is for the redshift decline of SSG for $z > 2.7$ and the dotted line is for a constant space density for $z > 1.5$. Note the observed excess of objects at $z < 1$. *Right:* Luminosity functions derived from *Chandra*, *ROSAT*, and *ASCA* surveys by Cowie et al. (2003), based on their redshift measurements and estimates. Note that the values for sources with $z < 1$ and $L_X < 10^{43}$ erg s^{-1} are well above those for the $2 < z < 4$ objects.

the XRB requires the existence of a substantial number of absorbed AGNs at relatively low redshifts (e.g., Gilli, Salvati, & Hasinger 2001, building on much previous work, such as that of Setti & Woltjer 1989).

Interestingly, optical identifications and follow-up spectroscopy are now demonstrating the presence of these sources (e.g., Barger et al. 2001; Hasinger private communication), which have generally escaped notice in previous surveys either because of their faintness or their unremarkable optical appearance and spectra. Cowie et al. (2003) and Hasinger (2004) have assembled large enough samples of objects to show clearly the excess of low-redshift AGNs compared to the expectations of the evolutionary fits found for the optical samples described above (Fig. 1.5). Martini et al. (2002) find an unexpectedly high fraction of X-ray selected AGNs in the cluster Abell 2104, only one of which has the characteristic emission lines of an AGN in its optical spectrum. These studies demonstrate the important power that deep X-ray observations bring to the studies of low-luminosity AGNs.

Thus, we are making good progress on mapping both the total contribution of AGNs to the X-ray background and the evolution with time of their X-ray emission, which in turn will lead to a measure of the accretion history of discrete sources in the Universe. We may look forward to substantial advances in the next decade as the observational data continue to improve and the physics of accretion is better understood.

1.7 Next Steps

In looking ahead, we can see that important next steps in this field include:

- Completing the mapping of the X-ray and optical luminosity functions for quasars and AGNs down to luminosities that include the bulk of the integrated radiation.
- Refining methods for mass determinations and applying them to the full observed range of redshifts and luminosities.
- Finding an observable spectral signature for accretion modes and efficiencies that will allow

us to make reliable estimates of accretion rates. Are low-luminosity AGNs a result of low accretion rate, low efficiency, or low mass?

- Determining the numbers of obscured sources and establishing the correlation between, for example, absorption in X-rays and UV/optical obscuration by dust. See if the results are consistent with deep radio and sub-mm observations.
- Achieving a self-consistent fit of the population of observed, discrete X-ray sources with the overall intensity level and SED of the X-ray background.

If, in the end, we can match the observational data for AGNs over their entire redshift range to the local mass function of black holes in galaxies, we will have made a significant leap in our understanding of the coevolution of black holes and galaxies.

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