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Invited Review

A Brief History of Active Galactic Nuclei

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ABSTRACT. Astronomers knew early in the 20th century that some galaxies have emission-line nuclei. However, even the 1943 systematic study by Seyfert was not enough to launch active galactic nuclei (AGN) as a major topic of astronomy. The advances in radio astronomy in the 1950s revealed a new universe of energetic phenomena and inevitably led to the discovery of quasars. These discoveries demanded the attention of observers and theorists, and AGN have been a subject of intense effort ever since. Only a year after the recognition of the redshifts of 3C 273 and 3C 48 in 1963, the idea of energy production by accretion onto a black hole was advanced. However, acceptance of this idea came slowly, encouraged by the discovery of black hole X-ray sources in our Galaxy and, more recently, supermassive black holes in the center of the Milky Way and other galaxies. Many questions remain as to the formation and fueling of the hole, the geometry of the central regions, the detailed emission mechanisms, the production of jets, and other aspects. The study of AGN will remain a vigorous part of astronomy for the foreseeable future.

1. INTRODUCTION

Although emission lines in the nuclei of galaxies were recognized at the beginning of the 20th century, a half-century more would pass before active galactic nuclei (AGN) became a focus of intense research effort. The leisurely pace of optical discoveries in the first half of the century gave way to the fierce competition of radio work in the 1950s. The race has never let up. Today, AGN are a focus of observational effort in every frequency band from radio to gamma rays. Several of these bands involve emission lines as well as continuum. AGN theory centers on extreme gravity and black holes, among the most exotic concepts of modern astrophysics. Ultrarelativistic particles, magnetic fields, hydrodynamics, and radiative transfer all come into play. In addition, AGN relate to the question of galactic evolution in general. For most of the time since the recognition of quasar redshifts in 1963, these objects have reigned as the most luminous and distant objects in the universe. Their use as probes of intervening matter on cosmic scales adds a further dimension to the importance of AGN.

For all these reasons, the enormous effort to describe and explain AGN in all their variety and complexity is quite natural. We are far from having a detailed and certain understanding of AGN. However, the working hypothesis that they involve at their core a supermassive black hole producing energy by accretion of gas has little serious competition today. If this picture is confirmed, then the past decade may be seen as a time when AGN research shifted from guessing the nature of AGN to trying to prove it.

Although the story is not finished, this seems a good time to take stock of the progress that has been made. The present short summary is intended to give students of AGN an account of some of the key developments in AGN research. The goal is to bring the story to the point where a contemporary review of AGN might begin its detailed discussion. Thus, various threads typically are followed to a significant point in the 1980s.

I have attempted to trace the important developments without excessive technical detail, relying on published sources, my own recollections, and conversations with a number of researchers. The focus is on the actual active nucleus. Fascinating aspects such as intervening absorption lines, statistical surveys, and links to galactic evolution receive relatively little discussion. The volume of literature is such that only a tiny fraction of the important papers can be cited.

2. BEGINNINGS

Early in the 20th century, Fath (1909) undertook at Lick Observatory a series of observations aimed at clarifying the nature of the "spiral nebulae." A major question at the time was whether spirals were relatively nearby, gaseous objects similar to the Orion Nebula, or very distant collections of unresolved stars. Fath's goal was to test the claim that spirals show a continuous spectrum consistent with a collection of stars, rather than the bright line spectrum charac-

teristic of gaseous nebulae. He constructed a spectrograph designed to record the spectra of faint objects, mounted it on the 36 inch Crossley reflector, and guided the long exposures necessary to obtain photographic spectra of these objects. For most of his objects, Fath found a continuous spectrum with stellar absorption lines, suggestive of an unresolved collection of solar-type stars. However, in the case of NGC 1068, he observed that the "spectrum is composite, showing both bright and absorption lines." The six bright lines were recognizable as ones seen in the spectra of gaseous nebulae.

The bright and dark lines of NGC 1068 were confirmed by Slipher (1917) with spectra taken in 1913 at Lowell Observatory. In 1917, he obtained a spectrum with a narrow spectrograph slit and found that the emission lines were not images of the slit but rather "small disks," i.e., the emission was spread over a substantial range of wavelengths. (However, he rejected an "ordinary radial velocity interpretation" of the line widths.) During the following years, several astronomers noted the presence of nuclear emission lines in the spectra of some spiral nebulae. For example, Hubble (1926) mentioned that the relatively rare spirals with stellar nuclei show a planetary nebula–type spectrum, notably, NGC 1068, 4051, and 4151.

The systematic study of galaxies with nuclear emission lines began with the work of Seyfert (1943). Seyfert obtained spectrograms of six galaxies with nearly stellar nuclei showing emission lines superimposed on a normal G-type (solar type) spectrum: NGC 1068, 1275, 3516, 4051, 4151, and 7469. The two brightest (NGC 1068 and 4151) showed "all the stronger emission lines ... in planetary nebulae like NGC 7027." Seyfert attributed the large widths of the lines to Doppler shifts, reaching up to 8500 km s^{-1} for the hydrogen lines of NGC 3516 and 7469. The emission-line profiles differed from line to line and from object to object, but two patterns were to prove typical of this class of galaxy. The forbidden and permitted lines in NGC 1068 had roughly similar profiles with widths of $\sim$3000 km s^{-1}. In contrast, NGC 4151 showed relatively narrow forbidden lines and corresponding narrow cores of the permitted lines, but the hydrogen lines had very broad (7500 km s^{-1}) wings that were absent from the profiles of the forbidden lines. Seyfert contrasted these spectra with the narrow emission lines of the diffuse nebulae (H II regions) seen in irregular galaxies and in the arms of spiral galaxies. Galaxies with high-excitation nuclear emission lines are now called "Seyfert galaxies." However, Seyfert's paper was not enough to launch the study of AGN as a major focus of astronomers' efforts. The impetus for this came from a new direction—the development of radio astronomy.

Jansky (1932), working at the Bell Telephone Laboratories, conducted a study of the sources of static affecting trans-Atlantic radio communications. Using a rotatable antenna and a shortwave receiver operating at a wavelength of 14.6 m, he systematically measured the intensity of the static arriving from all directions throughout the day. From these records, he identified three types of static: (1) static from local thunderstorms, (2) static from distant thunderstorms, and (3) "a steady hiss type static of unknown origin." The latter seemed to be somehow associated with the Sun (Jansky 1932). Continuing his measurements throughout the year, Jansky (1933) observed that the source of the static moved around in azimuth every 24 hours, and the time and direction of maximum changed gradually throughout the year in a manner consistent with the Earth's orbital motion around the Sun. He inferred that the radiation was coming from the center of the Milky Way Galaxy. After further study of the data, Jansky (1935) concluded that the radiation came from the entire disk of the Milky Way, being strongest in the direction of the Galactic center.

Few professional astronomers took serious note of Jansky's work, and it fell to an engineer, working at home in his spare time, to advance the subject of radio astronomy. Reber (1940a, 1940b) built a 31 foot reflector in his backyard near Chicago. He published a map of the radio sky at 160 MHz showing several local maxima, including one in the constellation Cygnus that would prove important for AGN studies (Reber 1944). He also noted that the ratio of radio radiation to optical light was vastly larger for the Milky Way than the Sun.

With the end of World War II, several groups of radio engineers turned their efforts to the study of radio astronomy. Notable among these were the groups at Cambridge and Manchester in England and at CSIRO in Australia. The study of discrete sources began with the accidental discovery of a small, fluctuating source in Cygnus by Hey, Parsons, & Phillips (1946) in the course of a survey of the Milky Way at 60 MHz. With their 6° beam, they set an upper limit of 2° on the angular diameter of the source. The intensity fluctuations, occurring on a timescale of seconds, were proved a few years later to originate in the Earth's ionosphere; but at first they served to suggest that the radiation "could only originate from a small number of discrete sources." The discrete nature of the Cygnus source was confirmed by Bolton & Stanley (1948), who used a sea-cliff interferometer to set an upper limit of 8′ to the width of the source. These authors deduced a brightness temperature of more than 4×10^6 K at 100 MHz and concluded that a thermal origin of the noise was "doubtful." Bolton (1948) published a catalog of six discrete sources and introduced the nomenclature Cyg A, Cas A, etc. Ryle & Smith (1948) published results from a radio interferometer at Cambridge analogous to the optical interferometer used by Michelson at Mount Wilson to measure stellar diameters. Observing at 80 MHz, they set an upper limit of 6′ to the angular diameter of the source in Cygnus.

Optical identifications of discrete sources (other than the Sun) were finally achieved by Bolton, Stanley, & Slee (1949).

Aided by more accurate positions from sea-cliff observations, they identified Taurus A with the Crab Nebula supernova remnant (M1); Virgo A with M87, a large elliptical galaxy with an optical jet; and Centaurus A with NGC 5128, an elliptical galaxy with a prominent dust lane. The partnership of optical and radio astronomy was underway.

The early 1950s saw progress in radio surveys, position determinations, and optical identifications. A class of sources fairly uniformly distributed over the sky was shown by the survey by Ryle, Smith, & Elsmore (1950) based on observations with the Cambridge interferometer. Smith (1951) obtained accurate positions of four discrete sources, Tau A, Vir A, Cyg A, and Cas A.

Smith's positions enabled Baade & Minkowski (1954) to make optical identifications of Cas A and Cyg A in 1951 and 1952. At the position of Cyg A, they found an object with a distorted morphology, which they proposed was two galaxies in collision. Baade & Minkowski found emission lines of [Ne v], [O ii], [Ne iii], [O iii], [O i], [N ii], and Hα, with widths of about 400 km s^{-1}. The redshift of 16,830 km s^{-1} implied a large distance, 31 Mpc, for the assumed Hubble constant of $H_0 = 540$ km s^{-1} Mpc^{-1}. The large distance of Cyg A implied an enormous luminosity, 8×10^{42} ergs s^{-1}, in the radio, larger than the optical luminosity of 6×10^{42} ergs s^{-1}. (Of course, these values are larger for a modern value of H_0.)

This period also saw progress in the measurement of the structure of radio sources. Hanbury Brown, Jennison, & Das Gupta (1952) reported results from the new intensity interferometer developed at Jodrell Bank, including a demonstration that Cyg A was elongated, with dimensions roughly $2' \times 0'.5$. Interferometer measurements of Cyg A by Jennison & Das Gupta (1953) showed two equal components separated by $1'.5$ that straddled the optical image, a puzzling morphology that proved to be common for extragalactic radio sources.

Radio sources were categorized as "Class I" sources, associated with the plane of the Milky Way, and "Class II" sources, isotropically distributed and possibly mostly extragalactic (e.g., Hanbury Brown 1959). Some of the latter had very small angular sizes, encouraging the view that many were "radio stars" in our Galaxy. Morris, Palmer, & Thompson (1957) published upper limits of $12''$ on the size of three Class II sources, implying brightness temperatures in excess of 2×10^7 K. They suggested that these were extragalactic sources of the Cyg A type.

Theoretically, Whipple & Greenstein (1937) attempted to explain the Galactic radio background measured by Jansky in terms of thermal emission by interstellar dust, but the expected dust temperatures were far too low to give the observed radio brightness. Reber (1940a) considered free-free emission by ionized gas in the interstellar medium. This process was considered more accurately by Henyey & Keenan (1940) and Townes (1947), who realized that Jansky's brightness temperature of $\sim 10^5$ K could not be reconciled with thermal emission from interstellar gas believed to have a temperature $\sim 10{,}000$ K. Alfvén & Herlofson (1950) proposed that "radio stars" involve cosmic-ray electrons in a magnetic field emitting by the synchrotron process. This quickly led Kiepenheuer (1950) to explain the Galactic radio background in terms of synchrotron emission by cosmic rays in the general Galactic magnetic field. He showed order-of-magnitude agreement between the observed and predicted intensities, supported by a more careful calculation by Ginzburg (1951). The synchrotron explanation became accepted for extragalactic discrete sources by the end of the 1950s. The theory indicated enormous energies, up to $\sim 10^{60}$ ergs for the "double-lobed" radio galaxies (Burbidge 1959). The confinement of the plasma in these lobes would later be attributed to ram pressure as the material tried to expand into the intergalactic medium (De Young & Axford 1967). A mechanism for production of bipolar flows to power the lobes was given by the "twin exhaust model" of Blandford & Rees (1974).

The third Cambridge (3C) survey at 159 MHz (Edge et al. 1959) was followed by the revised 3C survey at 178 MHz (Bennett 1962). Care was taken to minimize the confusion problems of earlier surveys, and many radio sources came to be known by their 3C numbers. These and the surveys that soon followed provided many accurate radio positions as the search for optical identifications accelerated. (AGN were also discovered in optical searches based on morphological "compactness" [Zwicky 1964] and strong ultraviolet continuum [Markarian 1967] and later infrared and X-ray surveys.) Source counts as a function of flux density ("log N–log S") showed a steeper increase in numbers with decreasing flux density than expected for a homogeneous, nonevolving universe with Euclidean geometry (e.g., Mills, Slee, & Hill 1958; Scott & Ryle 1961). This was used to argue against the "steady state" cosmology (Ryle & Clark 1961), although some disputed such a conclusion (e.g., Hoyle & Narlikar 1961).

3. THE DISCOVERY OF QUASARS

Minkowski's studies of radio galaxies culminated with identification of 3C 295 with a member of a cluster of galaxies at the unprecedented redshift of 0.46 (Minkowski 1960). Allan Sandage of the Mount Wilson and Palomar Observatories and Maarten Schmidt of the California Institute of Technology (Caltech) then took up the quest for optical identifications and redshifts of radio galaxies. Both worked with Thomas A. Matthews, who obtained accurate radio positions with the new interferometer at the Owens Valley Radio Observatory operated by Caltech. In 1960, Sandage obtained a photograph of 3C 48 showing a 16 mag

stellar object with a faint nebulosity. The spectrum of the object showed broad emission lines at unfamiliar wavelengths, and photometry showed the object to be variable and to have an excess of ultraviolet emission compared with normal stars. Several other apparently starlike images coincident with radio sources were found to show strange, broad emission lines. Such objects came to be known as quasi-stellar radio sources (QSRS), quasi-stellar sources (QSS), or quasars. Sandage reported the work on 3C 48 in an unscheduled paper in the 1960 December meeting of the AAS (summarized by the editors of *Sky & Telescope* [Matthews et al. 1961]). There was a "remote possibility that it may be a distant galaxy of stars" but "general agreement" that it was "a relatively nearby star with most peculiar properties."

The breakthrough came on 1963 February 5, as Schmidt was pondering the spectrum of the quasar 3C 273. An accurate position had been obtained in 1962 August by Hazard, Mackey, & Shimmins (1963), who used the 210 foot antenna at the Parkes station in Australia to observe a lunar occultation of 3C 273. From the precise time and manner in which the source disappeared and reappeared, they determined that the source had two components. 3C 273A had a fairly typical Class II radio spectrum, $F_\nu \sim \nu^{-0.9}$, and it was separated by 20″ from component B, which had a size less than 0.″5 and a "most unusual" spectrum, $f_\nu \sim \nu^{0.0}$. Radio positions B and A, respectively, coincided with those of a 13 mag starlike object and with a faint wisp or jet pointing away from the star. At first suspecting the stellar object to be a foreground star, Schmidt obtained spectra of it at the 200 inch telescope in late 1962 December. The spectrum showed broad emission lines at unfamiliar wavelengths, different from those of 3C 48. Clearly, the object was no ordinary star. Schmidt noticed that four emission lines in the optical spectrum showed a pattern of decreasing strength and spacing toward the blue, reminiscent of the Balmer series of hydrogen. He found that the four lines agreed with the expected wavelengths of Hβ, Hγ, Hδ, and Hϵ with a redshift of $z = 0.16$. This redshift in turn allowed him to identify a line in the ultraviolet part of the spectrum with Mg II λ2798. Schmidt consulted with his colleagues, Jesse L. Greenstein and J. B. Oke. Oke had obtained photoelectric spectrophotometry of 3C 273 at the 100 inch telescope, which revealed an emission line in the infrared at 7600 Å. With the proposed redshift, this feature agreed with the expected wavelength of Hα. Greenstein's spectrum of 3C 48 was explained with a redshift of $z = 0.37$, supported by the presence of Mg II in both objects. The riddle of the spectrum of quasars was solved.

These results were published in *Nature* 6 weeks later in adjoining papers by Hazard et al. (1963), Schmidt (1963), Oke (1963), and Greenstein & Matthews (1963). The objects might be Galactic stars with a very high density, giving a large gravitational redshift. However, this explanation was difficult to reconcile with the widths of the emission lines and the presence of forbidden lines. The "most direct and least objectionable" explanation was that the objects were extragalactic, with redshifts reflecting the Hubble expansion. The redshifts were large but not unprecedented; that of 3C 48 was second only to that of 3C 295. The radio luminosities of the two quasars were comparable with those of Cyg A and 3C 295. However, the optical luminosities were staggering, "10–30 times brighter than the brightest giant ellipticals," and the radio surface brightness was larger than for the radio galaxies. The redshift of 3C 273 implied a velocity of 47,400 km s^{-1} and a distance of about 500 Mpc (for $H_0 \approx 100$ km s^{-1} Mpc^{-1}). The nuclear region would then be less than 1 kpc in diameter. The jet would be about 50 kpc away, implying a timescale greater than 10^5 yr and a total energy radiated of at least 10^{59} ergs.

Before the redshift of 3C 273 was announced, Matthews & Sandage (1963) had submitted a paper identifying 3C 48, 3C 196, and 3C 286 with stellar optical objects. They explored the popular notion that these objects were some kind of Galactic star, arguing from their isotropic distribution on the sky and lack of observed proper motion that the most likely distance from the Sun was about 100 pc. The objects had peculiar colors, and 3C 48 showed light variations of 0.4 mag. In a section added following the discovery of the redshifts of 3C 273 and 3C 48, they pointed out that the size limit of ≤ 0.15 pc implied by the optical light variations was important in the context of the huge distance and luminosity implied by taking the redshift to result from the Hubble expansion.

A detailed analysis of 3C48 and 3C 273 was published by Greenstein & Schmidt (1964). They considered explanations of the redshift involving (1) rapid motion of objects in or near the Milky Way, (2) gravitational redshifts, and (3) cosmological redshifts. If 3C 273 had a transverse velocity comparable with the radial velocity implied by its redshift, the lack of an observed proper motion implied a distance of at least 10 Mpc (well beyond the nearest galaxies). The corresponding absolute magnitude was closer to the luminosity of galaxies than stars. The four quasars with known velocities were all receding, and accelerating a massive, luminous object to an appreciable fraction of the speed of light seemed difficult. Regarding gravitational redshifts, Greenstein & Schmidt argued that the widths of the emission lines required the line-emitting gas to be confined to a small fractional radius around the massive object producing the redshift. The observed symmetry of the line profiles seemed unnatural in a gravitational redshift model. For a 1 $M_\odot$ object, the observed Hβ flux implied an electron density $N_e \approx 10^{19}$ cm^{-3}, incompatible with the observed presence of forbidden lines in the spectrum. The emission-line constraint, together with a requirement that the massive object not disturb stellar orbits in the Galaxy, required a mass $\geq 10^9$ $M_\odot$. The stability of such a

"supermassive star" seemed doubtful in the light of theoretical work by Hoyle & Fowler (1963a), who had examined such objects as possible sources for the energy requirements of extragalactic radio sources. Adopting the cosmological explanation of the redshift, Greenstein & Schmidt derived radii for a uniform spherical emission-line region of 11 and 1.2 pc for 3C 48 and 3C 273, respectively. This was based on the Hβ luminosities and electron densities estimated from the Hβ, [O II], and [O III] line ratios. Invoking light travel time constraints based on the observed optical variability (Matthews & Sandage 1963; Smith & Hoffleit 1963), they proposed a model in which a central source of optical continuum was surrounded by the emission-line region and a still larger radio-emitting region. They suggested that a central mass of order $10^9\ M_\odot$ might provide adequate energy for the lifetime of $\geq 10^6$ yr implied by the jet of 3C 273 and the nebulosity of 3C 48. This mass was about right to confine the line-emitting gas, which would disperse quickly if it expanded at the observed speeds of 1000 km s^{-1} or more. Noting that such a mass would correspond to a Schwarzschild radius of $\sim 10^{-4}$ pc, they observed that "it would be important to know whether continued energy and mass input from such a 'collapsed' region are possible." Finally, they noted that there could be galaxies around 3C 48 and 3C 273 hidden by the glare of the nucleus. Many features of this analysis are recognizable in current thinking about AGN.

The third and fourth quasar redshifts were published by Schmidt & Matthews (1964), who found $z = 0.425$ and 0.545 for 3C 47 and 3C 147, respectively. Schmidt (1965) published redshifts for five more quasars. For 3C 254, a redshift $z = 0.734$, based on several familiar lines, allowed the identification of C III] λ1909 for the first time. This in turn allowed the determination of redshifts of 1.029 and 1.037 from λ1909 and λ2798 in 3C 245 and CTA 102, respectively. (CTA is a radio source list from the Caltech radio observatory.) For 3C 287, a redshift of 1.055 was found from λ1909, λ2798, and another first, C IV λ1550. Finally, a dramatically higher redshift of 2.012 was determined for 3C 9 on the basis of λ1550 and the first detection of the Lyα line of hydrogen at λ1215. The redshifts were large enough that the absolute luminosities depended significantly on the cosmological model used.

Sandage (1965) reported the discovery of a large population of radio-quiet objects that otherwise appeared to resemble quasars. Matthews & Sandage (1963) had found that quasars showed an "ultraviolet excess" when compared with normal stars on a color-color ($U-B$, $B-V$) diagram. This led to a search technique in which exposures in U and B were recorded on the same photographic plate, with a slight positional offset, allowing rapid identification of objects with strong ultraviolet continua. Sandage noticed a number of such objects that did not coincide with known radio sources. These he called "interlopers," "blue stellar objects" (BSO), or "quasi-stellar galaxies" (QSG).[1] Sandage found that at magnitudes fainter than 15, the UV-excess objects populated the region occupied by quasars on the color-color diagram, whereas brighter objects typically had the colors of main-sequence stars. The number counts of the BSOs as a function of apparent magnitude also showed a change of slope at $\sim$15 mag, consistent with an extragalactic population of objects at large redshift. Spectra showed that many of these objects indeed had spectra with large redshifts, including $z = 1.241$ for BSO 1. Sandage estimated that the QSGs outnumbered the radio-loud quasars by a factor $\sim$500, but this was reduced by later work (e.g., Kinman 1965; Lynds & Villere 1965).

The large redshifts of QSOs immediately made them potential tools for the study of cosmological questions. The rough similarity of the emission-line strengths of QSOs to those observed, or theoretically predicted, for planetary nebulae suggested that the chemical abundances were roughly similar to those in our Galaxy (Sklovskii 1964; Osterbrock & Parker 1966). Thus these objects, suspected by many astronomers to lie in the nuclei of distant galaxies, had reached fairly "normal" chemical compositions when the universe was considerably younger than today.

The cosmological importance of redshifts high enough to make Lyα visible was quickly recognized. Hydrogen gas in intergalactic space would remove light from the quasar's spectrum at the local cosmological redshift, and continuously distributed gas would erase a wide band of continuum to the short-wavelength side of the Lyα emission line (Gunn & Peterson 1965; Scheuer 1965). Gunn & Peterson set a tight upper limit to the amount of neutral hydrogen in intergalactic space, far less than the amount that would significantly retard the expansion of the universe.

The study of discrete absorption features in quasar spectra also began to develop. An unidentified sharp line was observed in the spectrum of 3C 48 by Greenstein & Schmidt (1964). Sandage (1965) found that the λ1550 emission line of BSO 1 was "bisected by a sharp absorption feature." The first quasar found with a rich absorption spectrum was 3C 191 (Burbidge, Lynds, & Burbidge 1966; Stockton & Lynds 1966). More than a dozen sharp lines were identified, including Lyα and lines of C II, III, and IV and Si II, III, and IV. A rich set of narrow absorption lines was also observed in the spectrum of PKS 0237$-$23, whose emission-line redshift, $z = 2.223$, set a record at the time. Arp, Bolton, & Kinman (1967) and Burbidge (1967a), respectively, proposed absorption-line redshifts of $z = 2.20$ and 1.95 for this object, but each value left many lines without satisfactory identifications. It turned out that both redshifts were present (Greenstein & Schmidt 1967).

[1] Here we adopt the now common practice of using the term "quasi-stellar object" (QSO) to refer to these objects regardless of radio luminosity (Burbidge & Burbidge 1967).

All these absorption systems had $z_{abs} < z_{em}$. They could be interpreted as intervening clouds imposing absorption spectra at the appropriate cosmological redshift, as had been anticipated theoretically (Bahcall & Salpeter 1965). Alternatively, they might represent material expelled from the quasar, whose outflow velocity is subtracted from the cosmological velocity of the QSO. However, PKS 0119−04 was found to have $z_{abs} > z_{em}$, implying material that was in some sense falling into the QSO from the near side with a relative velocity of 10^3 km s^{-1} (Kinman & Burbidge 1967). Today, a large fraction of the narrow absorption lines with z_{abs} substantially less than z_{em} are believed to result from intervening material. This includes the so-called Lyα forest of closely spaced, narrow Lyα lines that punctuate the continuum to the short-wavelength side of the Lyα emission line, especially in high-redshift QSOs. The study of intervening galaxies and gas clouds by means of absorption lines in the spectra of background QSOs is now a major branch of astrophysics.

A different kind of absorption was discovered in the spectrum of PHL 5200 by Lynds (1967). This object showed broad absorption bands on the short-wavelength sides of the Lyα, N v λ1240, and C iv λ1550 emission lines, with a sharp boundary between the emission and absorption. Lynds interpreted this in terms of an expanding shell of gas around the central object. Seen in about 10% of radio-quiet QSOs (Weymann et al. 1991), these broad absorption lines (BALs) are among the many dramatic but poorly understood aspects of AGN.

The huge luminosity of QSOs, rapid variability, and implied small size caused some astronomers to question the cosmological nature of the redshifts. Terrell (1964) considered the possibility that the objects were ejected from the center of our Galaxy. Upper limits on the proper motion of 3C 273, together with a Doppler interpretation of the redshift, then implied a distance of at least 0.3 Mpc and an age at least 5 million years. Arp (1966), pointing to close pairs of peculiar galaxies and QSOs on the sky, argued for non-cosmological redshifts that might result from ejection from the peculiar galaxies at high speeds or an unknown cause. Setti & Woltjer (1966) noted that ejection from the Galactic center would imply for the QSO population an explosion with energy at least 10^{60} ergs, and more if ejected from nearby radio galaxies such as Cen A as suggested by Hoyle & Burbidge (1966). Furthermore, Doppler boosting would cause us to see more blueshifts than redshifts if the objects were ejected from nearby galaxies (Faulkner, Gunn, & Peterson 1966). Further evidence for cosmological redshifts was provided by Gunn (1971), who showed that two clusters of galaxies containing QSOs had the same redshifts as the QSOs. Also, Kristian (1973) showed that the "fuzz" surrounding the quasi-stellar image of a sample of QSOs was consistent with the presence of a host galaxy.

4. CHARTING THE TERRAIN

At this stage, a number of properties of AGN were recognized. Most astronomers accepted the cosmological redshift of QSOs, and the parallel between Seyfert galaxies and QSOs suggested a common physical phenomenon. Questions included the nature of the energy source, the nature of the continuum source and emission-line regions, and the factors that produce an AGN in some galaxies and not others.

4.1. Emission Lines

The basic parameters of the region of gas emitting the narrow emission lines were fairly quickly established. In one of the first physical analyses of "emission nuclei" in galaxies, Woltjer (1959) derived a density $N_e \approx 10^4$ cm^{-3} and temperature $T \approx 20{,}000$ K from the [S ii] and [O iii] line ratios of Seyfert galaxies. The region emitting the narrow lines was just resolved for the nearest Seyfert galaxies, giving a diameter of order 100 pc (e.g., Walker 1968; Oke & Sargent 1968). Oke & Sargent derived a mass of $\sim 10^5\ M_\odot$ and a small volume filling factor for the narrow line gas in NGC 4151. Burbidge, Burbidge, & Prendergast (1958) found that the nuclear emission lines of NGC 1068 were much broader than could be accounted for by the rotation curve of the galaxy and concluded that the material was in a state of expansion.

A key question was why, in objects showing broad wings, these were seen on the permitted lines but not the forbidden lines. (Seyfert galaxies with broad wings came to be called "Seyfert 1" or "Sy 1" and those without them "Sy 2" [Khachikian & Weedman 1974].) Were these wings emitted by the same gas that emits the narrow lines? Woltjer (1959) postulated a separate region of fast-moving, possibly gravitationally bound gas to produce the broad Balmer line wings of Seyfert galaxies. Souffrin (1969a) adopted such a model in her analysis of NGC 3516 and NGC 4151. Alternatively, broad Balmer line wings might be produced by electron scattering (Burbidge et al. 1966). Oke & Sargent (1968) supported this possibility for NGC 4151. Their analysis of the emission-line region gave an electron scattering optical depth $\tau_e \sim 0.1$. Multiple scattering of Balmer line photons by the line opacity might increase the effective electron scattering probability, explaining the presence of wings only on the permitted lines. However, analysis of electron scattering profiles by other authors (e.g., Weymann 1970) indicated the need for a dense region only a tiny fraction of a light year across. Favoring mass motions were the irregular broad line profiles in some objects (Anderson 1971), which demonstrated the presence of bulk velocities of the needed magnitude. In addition, Shklovskii (1964) had argued for an electron scattering optical depth $\tau_{es} < 1$ in 3C 273 to avoid excessive smoothing of the continuum light

variations. The picture of broad lines from a small region of dense, fast-moving clouds ("broad line region" or BLR) and narrow lines from a larger region of slower moving, less dense clouds ("narrow line region" or NLR) found support from photoionization modes (Shields 1974).

Early workers (e.g., Seyfert 1943) had noted that the narrow line intensities resembled those of planetary nebulae, and photoionization was an obvious candidate for the energy input to the emitting gas for both the broad and narrow lines. For 3C 273, Shklovskii (1964) noted that the kinetic energy of the emission-line gas could power the line emission only for a very short time, whereas the extrapolated power in ionizing ultraviolet radiation was in rough agreement with the emission-line luminosities. Osterbrock & Parker (1965) argued against photoionization because of the observed weakness of the Bowen O III fluorescence lines. Also eliminating thermal collisional ionization because of the observed wide range of ionization stages, they proposed ionization and heating by fast protons resulting from high-velocity cloud collisions. Souffrin (1969b) rejected this on the basis of thermal equilibrium considerations and argued along with Williams & Weymann (1968) that thermal collisional ionization was inconsistent with observed temperatures. Noting that an optical–ultraviolet continuum of roughly the needed power is observed, and that the thermal equilibrium gives roughly the observed temperature, Souffrin concluded that a nonthermal ultraviolet continuum was "the only important source of ionization." Searle & Sargent (1968) likewise noted that the equivalent widths of the broad Hβ emission lines were similar among AGN over a wide range of luminosity and were consistent with an extrapolation of the observed "nonthermal" continuum as a power law to ionizing frequencies. Detailed models of gas clouds photoionized by a power-law continuum were calculated with the aid of electronic computers, with application to the Crab Nebula, binary X-ray sources, and AGN (Williams 1967; Tarter & Salpeter 1969; Davidson 1972; MacAlpine 1972). Such models showed that photoionization can account for the intensities of the strongest optical and ultraviolet emission lines. In particular, the penetrating high-frequency photons can explain the simultaneous presence of very high ionization stages and strong emission from low-ionization stages, in the context of a "nebula" that is optically thick to the ionizing continuum. Photoionization quickly became accepted as the main source of heating and ionization in the emission-line gas.

Attention then focused on improving photoionization models and understanding the geometry and dynamics of the gas emitting the broad lines. It was clear that the emitting gas had only a tiny volume filling factor, and one possible possible geometry was the traditional nebular picture of clouds or "filaments" scattered through the BLR volume. Photoionization models typically assumed a slab geometry representing the ionized face of a cloud that was optically thick to the Lyman continuum. Model parameters included the density and chemical composition of the gas and the intensity and energy distribution of the incident ionizing continuum. Various line ratios, such as C III]/C IV, were used to constrain the "ionization parameter," i.e., the ratio of ionizing photon density to gas density. Chemical abundances were assumed to be approximately solar but were hard to determine because the high densities prevented a direct measurement of the electron temperature from available line ratios.

A challenge for photoionization models was the discovery that the Lyα/Hα ratio was an order of magnitude smaller than the value of ~ 50 predicted by photoionization models at the time (Baldwin 1977a; Davidsen, Hartig, & Fastie 1977). This stimulated models with an improved treatment of radiative transfer in optically thick hydrogen lines (e.g., Kwan & Krolik 1979). These models found strong Balmer line emission from a "partially ionized zone" deep in the cloud, heated by penetrating X-rays, from which Lyman line emission was unable to escape. The models still did not do a perfect job of explaining the observed ratios (e.g., Lacy et al. 1982) of the Paschen, Balmer, and Lyman lines. Models by Collin-Souffrin, Dumont, & Tully (1982) and Wills, Netzer, & Wills (1985) suggested the need for densities as high as $N_e \approx 10^{11}$ cm^{-3} to explain the Hα/Hβ ratio.

The X-ray–heated region also was important for the formation of the strong Fe II multiplet blends observed in the optical and ultraviolet. Theoretical efforts by several authors culminated in models involving thousands of Fe lines, with allowance for the fluorescent interlocking of different lines (Wills et al. 1985). These models enjoyed some success in explaining the relative line intensities, but the total energy in the Fe II emission was less than observed. Although some of this discrepancy might involve the iron abundance, Collin-Souffrin et al. (1980) proposed a separate Fe II–emitting region with a high density ($N_e \approx 10^{11}$ cm^{-3}) heated by some means other than photoionization. This region might be associated with an accretion disk. The Fe II emission and the Balmer continuum emission that combined to form the 3000 Å "little bump" still are not fully explained, nor is the tendency for radio-loud AGN to have weaker Fe II and steeper Balmer decrements than radio-quiet objects (Osterbrock 1977).

A tendency for the equivalent width of the C IV emission line to decrease with increasing luminosity was found by Baldwin (1977b). Explanations of this involved a possible decrease, with increasing luminosity, in the ionization parameter and in the "covering factor," i.e., the fraction ($\Omega/4\pi$) of the ionizing continuum intercepted by the BLR gas (Mushotzky & Ferland 1984). The ionization parameter was also the leading candidate to explain the difference in ionization level between classical Seyfert galaxies and the "low-ionization nuclear emission regions" or "LINERs"

(Heckman 1980; Ferland & Netzer 1983; Halpern & Steiner 1983).

The geometry and state of motion of the BLR gas has been a surprisingly stubborn problem. If the BLR was a swarm of clouds, they might be falling in (possibly related to the accretion supply), orbiting, or flying out. Alternatively, the gas might be associated with an accretion disk irradiated by the ionizing continuum (e.g., Shields 1977; Collin-Souffrin 1987). Except for the BAL QSOs, there was little evidence for blueshifted absorption analogous to the P Cygni–type line profiles of stars undergoing vigorous mass loss. The approximate symmetry of optically thick lines such as Lyα and Hα suggested that the motion was circular or random rather than predominantly radial (e.g., Ferland, Netzer, & Shields 1979). However, for orbiting (or infalling) gas, the line widths implied rather large masses for the central object, given prevailing estimates of the BLR radius. In addition, gas in Keplerian orbit seemed likely to give a double-peaked line profile or to have other problems (Shields 1978a). In the face of these conflicting indications, the most common assumption was that the gas took the form of clouds flying outward from the central object. The individual clouds would disperse quickly unless confined by some intercloud medium, and a possible physical model was provided by the two-phase medium discussed by Krolik, McKee, & Tarter (1981). Radiation pressure of the ionizing continuum, acting on the bound-free opacity of the gas, seemed capable of producing the observed velocities and giving a natural explanation of the "logarithmic" shape of the observed line profiles (Mathews 1974; Blumenthal & Mathews 1975). Interpretation of the line profiles was complicated by the recognition of systematic offsets in velocity between the high- and low-ionization lines (Gaskell 1982; Wilkes & Carswell 1982; Wilkes 1984).

A powerful new tool was provided by the use of "echo mapping" or "reverberation mapping" of the BLR. Echo mapping relies on the time delays between the continuum and line variations caused by the light travel time across the BLR (Blandford & McKee 1982). Early results showed that the BLR is smaller and denser than most photoionization models had indicated (Ulrich et al. 1984; Peterson et al. 1985). Masses of the central object, by this time assumed to be a black hole, could be derived with increased confidence. The smaller radii implied smaller masses that seemed reasonable in the light of other considerations, and the idea of gravitational motions for the BLR gained in popularity. This was supported by the rough tendency of the line profiles to vary symmetrically, consistent with "chaotic" or circular motions (e.g., Ulrich et al. 1984).

4.2. Energy Source

The question of the ultimate energy source for AGN stimulated creativity even before the discovery of QSO redshifts. The early concept of radio galaxies as galaxies in collision gave way to the recognition of galactic nuclei as the sites of concentrated, violent activity. Burbidge (1961) suggested that a chain reaction of supernovae (SN) could occur in a dense star cluster in a galactic nucleus. Shock waves from one SN would compress neighboring stars, triggering them to explode in turn. Cameron (1962) considered a coeval star cluster leading to a rapid succession of SN as the massive stars finished their short lives. Spitzer & Saslaw (1966), building on earlier suggestions, developed another model involving a dense star cluster. The cluster core would evolve to higher star densities through gravitational "evaporation," and this would lead to frequent stellar collisions and tidal encounters, liberating large amounts of gas. Additional ideas involving dense star clusters included pulsar swarms (Arons, Kulsrud, & Ostriker 1975) and starburst models (Terlevich & Melnick 1985).

Hoyle & Fowler (1963a, 1963b) discussed the idea of a supermassive star (up to $\sim 10^8\ M_\odot$) as a source of gravitational and thermonuclear energy. In additional to producing large amounts of energy per unit mass, all these models seemed capable of accelerating particles to relativistic energies and producing gas clouds ejected at speeds of ~ 5000 km s^{-1}, suggestive of the broad emission line wings of Seyfert galaxies. In this regard, Hoyle & Fowler (1963a) suggested that "a magnetic field could be wound toroidally between the central star and a surrounding disk." The field could store a large amount of energy, leading to powerful "explosions" and jets like that of M87. Hoyle & Fowler (1963b) suggested that "only through the contraction of a mass of 10^7–$10^8\ M_\odot$ to the relativistic limit can the energies of the strongest sources be obtained."

Soon after, Salpeter (1964) and Zeldovich (1964) proposed the idea of QSO energy production from accretion onto a supermassive black hole. For material gradually spiraling to the innermost stable orbit of a nonrotating black hole at $r = 6GM/c^2$, the energy released per unit mass would be $0.057c^2$, enough to provide the energy of a luminous QSO from a reasonable mass. Salpeter imagined some kind of turbulent transport of angular momentum, allowing the matter to move closer to the hole, which would grow in mass during the accretion process.

The black hole model received limited attention until Lynden-Bell (1969) argued that dead quasars in the form of "collapsed bodies" (black holes) should be common in galactic nuclei, given the lifetime energy output of quasars and their prevalence at earlier times in the history of the universe. Quiescent ones might be detectable through their effect on the mass-to-light ratio of nearby galactic nuclei. Lynden-Bell explored the thermal radiation and fast particle emission to be expected in a disk of gas orbiting the hole, with energy dissipation related to magnetic and turbulent processes. For QSO luminosities, the disk would have a maximum effective temperature of $\sim 10^5$ K, possibly

leading to photoionization and broad line emission. He remarked that "with different values of the [black hole mass and accretion rate] these disks are capable of providing an explanation for a large fraction of the incredible phenomena of high-energy astrophysics, including galactic nuclei, Seyfert galaxies, quasars and cosmic rays."

Further evidence for relativistic conditions in AGN came from other theoretical arguments. Hoyle, Burbidge, & Sargent (1966) noted that relativistic electrons emitting optical and infrared synchrotron radiation would also Compton scatter ambient photons, boosting their energy by large factors. This would lead to "repeated stepping up of the energies of quanta," yielding a divergence that came to be known as the "inverse Compton catastrophe." This would be attended by rapid quenching of the energy of the electrons. They argued that this supported the idea of noncosmological redshifts. In response, Woltjer (1966) invoked a model with electrons streaming radially on field lines, which could greatly reduce Compton losses. He further noted that because "the relativistic electrons and the photons they emit both move nearly parallel to the line of sight, the time scale of variations in emission can be much shorter than the size of the region divided by the speed of light." The emission would also likely be anisotropic, reducing the energy requirements for individual objects.

4.3. Superluminal Motion

Dramatic confirmation of the suspected relativistic motions came from the advancing technology of radio astronomy. Radio astronomers using conventional interferometers had shown that many sources had structure on a subarcsecond scale. Scintillation of the radio signal from some AGN, caused by the interplanetary medium of our solar system, also implied subarcsecond dimensions (Hewish, Scott, & Wills 1964). The compact radio sources in some AGN showed flat spectrum components and variability on timescales of months (Dent 1965; Sholomitsky 1965). The variability suggested milliarcsecond dimensions on the basis of light travel time arguments. The spectral shape and evolution found explanation in terms of multiple, expanding components that were optically thick to synchrotron self-sbsorption, which causes a low-frequency cutoff in the emitted continuum (Pauliny-Toth & Kellermann 1966, and references therein). Such models had interesting theoretical consequences, including angular sizes (for cosmological redshifts) as small as 10^{-3} arcsec, and large amounts of energy in relativistic electrons, far exceeding the energy in the magnetic field.

These inferences made clear the need for angular resolution finer than was practical with conventional radio interferometers connected by wires or microwave links. This was achieved by recording the signal from the two antennas separately on magnetic tape, and correlating the recorded signals later by analog or digital means. This technique came to be known as "very long baseline interferometry" (VLB, later VLBI). After initial difficulties finding "fringes" in the correlated signal, competing groups in Canada and the United States succeeded in observing several AGN in the spring of 1967, over baselines of roughly 200 km (see Cohen et al. 1968). The U.S. experiments typically used the 140 foot antenna at the National Radio Astronomy Observatory in Green Bank, West Virginia, in combination with increasingly remote antennas in Maryland, Puerto Rico, Massachusetts, California, and Sweden. The latter gave an angular resolution of 0.″0006. Within another year, observations were made between Owens Valley, California, and Parkes, Australia, a baseline exceeding 10,000 km or 80% of the Earth's diameter. A number of AGN showed components unresolved on a scale of 10^{-3} arcsec.

On 1970 October 14 and 15, Knight et al. (1971) observed quasars at 7840 MHz with the Goldstone, California–Haystack, Massachusetts, "Goldstack" baseline. 3C 279 showed fringes consistent with a symmetrical double source separated by $(1.55 \pm 0.03) \times 10^{-3}$ arcsec. Later observations on 1971 February 14 and 26 by Whitney et al. (1971) showed a double source structure at the same position angle, but separated by a distinctly larger angle of $(1.69 \pm 0.02) \times 10^{-3}$ arcsec. Given the distance implied by the redshift of 0.538, this rate of angular separation corresponded to a linear separation rate of 10 times the speed of light! Cohen et al. (1971), also using Goldstack data, observed "superlight expansion" in 3C 273 and 3C 279. Whitney et al. and Cohen et al. considered a number of interpretations of their observations, including multiple components that blink on and off (the "Christmas tree model") and noncosmological redshifts. However, most astronomers quickly leaned toward an explanation involving motion of emitting clouds ejected from the central object at speeds close to, but not exceeding, the speed of light. Rees (1966) had calculated the appearance of relativistically expanding sources, and apparent expansion speeds faster than that of light were predicted. A picture emerged in which a stationary component was associated with the central object, and clouds were ejected at intervals of several years along a fairly stable axis. (Repeat ejections were observed in the course of time by VLBI experiments.) If this ejection occurred in both directions, it could supply energy to the extended double sources. The receding components would be greatly dimmed by special relativistic effects, while the approaching components were brightened. The two observed components are then associated with the central object and the approaching cloud, respectively. The fact that the two observed components had roughly equal luminosities found an explanation in the relativistic jet model of Blandford & Königl (1979).

Apparent superluminal motion has now been seen in a number of quasars and radio galaxies, and a possibly analogous phenomenon has been observed in connection with black hole systems of stellar mass in our Galaxy (Mirabel & Rodriguez 1994).

4.4. X-Rays from AGN

On 1962 June 18, an Aerobee sounding rockets blasted skyward from White Sands proving ground in New Mexico. It carried a Geiger counter designed to detect astronomical sources of X-rays. The experiment, carried out by Giacconi et al. (1962), discovered an X-ray background and a "large peak" in a 10° error box near the Galactic center and the constellation Scorpius. A rocket experiment by Bowyer et al. (1964) also found an isotropic background, confirmed the Scorpius source, and detected X-rays from the Crab Nebula. Friedman & Byram (1967) identified X-rays from the active galaxy M87. A rocket carrying collimated proportional counters sensitive in the 1–10 keV energy range, found sources coincident with 3C 273, NGC 5128 (Cen A), and M87 (Bowyer, Lampton, & Mack 1970). The positional error box for 3C 273 was small enough to give a probability of less that 10^{-3} of a chance coincidence. The X-ray luminosity, quoted as $\sim 10^{46}$ ergs s^{-1}, was comparable with quasar's optical luminosity.

The first dedicated X-ray astronomy satellite, *Uhuru*, was launched in 1970. Operating until 1973, it made X-ray work a major branch of astronomy. X-rays were reported from the Seyfert galaxies NGC 1275 and NGC 4151 (Gursky et al. 1971). The spectrum of NGC 5128 was consistent with a power law of energy index $\alpha = -0.7$, where $L_\nu \propto \nu^\alpha$; and there was low energy absorption corresponding to a column density of 9×10^{22} atoms cm^{-2}, possibly caused by gas in the nucleus (Tucker et al. 1973). Early variability studies were hampered by the need to compare results from different experiments, but Winkler & White (1975) found a large change in the flux from Cen A in only 6 days from *OSO 7* data. Using *Ariel V* observations of NGC 4151, Ives, Sanford, & Penston (1976) found a significant increase in flux from earlier *Uhuru* measurements. Marshall, Warwick, & Pounds (1981), using Ariel V data on AGN gathered over a 5 year period, found that roughly half of the sources varied by up to a factor of 2 on times less than or equal to a year. A number of sources varied in times of 0.5–5 days. Marshall et al. articulated the importance of X-ray variability observations, which show that the X-rays "arise deep in the nucleus" and "relate therefore to the most fundamental aspect of active galaxies, the nature of the central 'power house'."

Strong X-ray emission as a characteristic of Sy 1 galaxies was established by Martin Elvis and his coworkers from *Ariel V* data (Elvis et al. 1978). This work increased to 15 the number of known Seyfert X-ray sources, of which at least three were variable. Typical luminosities were $\sim 10^{42.5}$–$10^{44.5}$ ergs s^{-1}. The X-ray power correlated with the infrared and optical continuum and Hα line. Seyfert galaxies evidently made a significant contribution to the X-ray background, and limits could be set on the evolution of Seyfert galaxy number densities and X-ray luminosities in order that they not exceed the observed background. Elvis et al. considered thermal bremsstrahlung (10^7 K), synchrotron, and synchrotron self-Compton models of the X-ray emission.

HEAO 1, the first of the *High Energy Astronomy Observatories*, was an X-ray facility that operated from 1977 to 1979. It gathered data on a sufficient sample of objects to allow comparisons of different classes of AGN and to construct a log N–log S diagram and improved luminosity function. *HEAO 1* provided broad-band X-ray spectral information for a substantial set of AGN, showing spectral indices $\alpha \approx -0.7$, with rather little scatter, and absorbing columns less than 5×10^{22} cm^{-2} (Mushotzky et al. 1980).

The *Einstein Observatory* (*HEAO 2*) featured grazing incidence focusing optics allowing detection of sources as faint as $\sim 10^{-7}$ the intensity of the Crab Nebula. Tananbaum et al. (1979) used *Einstein* data to study QSOs as a class of X-ray emitters. Luminosities of 10^{43}–10^{47} ergs s^{-1} (0.5–4.5 keV) were found. OX 169 varied substantially in under 10,000 s, indicating a small source size. This suggested a black hole mass not greater than 2×10^8 $M_\odot$, if the X-rays came from the inner portion of an accretion flow. By this time, strong X-ray emission was established as a characteristic of all types of AGN and a valuable diagnostic of their innermost workings.

4.5. The Continuum

Today, the word "continuum" in the context of AGN might bring to mind anything from radio to gamma-ray frequencies. However, in the early days of QSO studies, the term generally meant the optical continuum, extending to the ultraviolet and infrared as observations in these bands became available. Techniques of photoelectric photometry and spectrum scanning were becoming established as QSO studies began. The variability of QSOs, including 3C 48 and 3C 273 (e.g., Sandage 1963), was known and no doubt contributed to astronomers' initial hesitation to interpret QSO spectra in terms of large redshifts. In his contribution to the four discovery papers on 3C 273, Oke (1963) presented spectrophotometry showing a continuum slope $L_\nu \propto \nu^{+0.3}$ in the optical, becoming redder toward the near-infrared. He noted that the energy distribution did not resemble a blackbody, and inferred that there must be a substantial contribution of synchrotron radiation.

A key issue for continuum studies has been the relative importance of thermal and nonthermal emission processes in various wavebands. Early work tended to assume syn-

chrotron radiation, or "nonthermal emission," in the absence of strong evidence to the contrary. The free-free and bound-free emission from the gas producing the observed emission lines was generally a small contribution. The possibility of thermal emission from very hot gas was considered for some objects such as the flat blue continuum of 3C 273 (e.g., Oke 1966). The energy distributions tend to slope up into the infrared; and for thermal emission from optically thin gas, this would would have required a rather low temperature and an excessive Balmer continuum jump. This left the possibilities of nonthermal emission or thermal emission from warm dust, presumably heated by the ultraviolet continuum.

Observational indicators of thermal or nonthermal emission include broad features in the energy distribution, variability, and polarization. For the infrared, one also has correlations with reddening, the silicate absorption and emission features, and possible angular resolution of the source (Edelson et al. 1988). For some objects, rapid optical variability implied brightness temperatures that clearly required a nonthermal emission mechanism. For example, Oke (1967) observed day-to-day changes of 0.25 and 0.1 mag for 3C 279 and 3C 446, respectively. For many objects, the energy distributions were roughly consistent with a power law of slope near $\nu^{-1.2}$. Power laws of similar slopes were familiar from radio galaxies and the Crab Nebula, where the emission extended through the optical band. These spectra were interpreted in terms of synchrotron radiation with power-law energy distributions for the radiating, relativistic electrons. Such a power-law energy distribution was also familiar from studies of cosmic rays, and thus power laws seemed natural in the context of high-energy phenomena like AGN. In addition to simple synchrotron radiation, there might be a hybrid process involving synchrotron emission in the submillimeter and far-infrared, with some of these photons boosted to the optical by "inverse" Compton scattering (Shklovskii 1965). The idea of a nonthermal continuum in the optical, whose high-frequency extrapolation provided the ionizing radiation for the emission-line regions, was widely held for many years. This was invoked not only for QSOs but also for Seyfert galaxies, where techniques such as polarization were used to separate the "nonthermal" and galaxy components (e.g., Visvanathan & Oke 1968).

Infrared observations were at first plagued by low sensitivity and inadequate telescope apertures. Measurements of 3C 273 in the K filter (2.2 μm), published by Johnson (1964) and Low & Johnson (1965), showed a continuum steeply rising into the infrared. Infrared radiation from NGC 1068 was observed by Pacholczyk & Wisniewski (1967), also with a flux density (F_ν) strongly rising to the longest wavelength observed ("N" band, or 10 μm). The infrared radiation dominated the power output of this object. Becklin et al. (1973) found that much of the 10 μm emission from NGC 1068 came from a resolved source 1″ (90 pc) across and concluded that most of the emission was not synchrotron emission. In contrast, variability of the 10 μm emission from 3C 273 (e.g., Rieke & Low 1972) pointed to a strong nonthermal component. Radiation from hot dust has a minimum source size implied by the blackbody limit on the surface brightness, and this is more stringent for longer wavelengths radiated by cooler dust. This in turn implies a minimum variability timescale as a function of wavelength. The near-infrared emission of NGC 1068 was found to be strongly polarized (Knacke & Capps 1974).

Improving infrared technology, and optical instruments such as the multichannel spectrometer on the 200 inch telescope (Oke 1969), led to larger and better surveys of the AGN continuum. Oke, Neugebauer, & Becklin (1970) reported observations of 28 QSOs from 0.3 to 2.2 μm. The energy distributions were similar in radio-loud and radio-quiet QSOs. They found that the energy distributions could generally be described as a power law (index -0.2 to -1.6 for $F_\nu \propto \nu^\alpha$) and that they remained "sensibly unchanged" during the variations of highly variable objects. Penston et al. (1974) studied the continuum from 0.3 to 3.4 μm in 11 bright Seyfert galaxies. All turned up toward the infrared, and consideration of the month-to-month variability pointed to different sources for the infrared and optical continua. From an extensive survey of Seyfert galaxies, Rieke (1978) concluded that strong infrared emission was a "virtually universal" feature and that the energy distributions in general did not fit a simple power law. The amounts of dust required were roughly consistent with the expected dust in the emission-line gas of the active nucleus and the surrounding interstellar medium. A consensus emerged that the infrared emission of Seyfert 2 galaxies was thermal dust emission, but the situation for Seyfert 1 galaxies was less clear (e.g., Neugebauer et al. 1976; Stein & Weedman 1976). From a survey of the optical and infrared energy distribution of QSOs, Neugebauer et al. (1979) concluded that the slope was steeper in the 1–3 μm band than in the 0.3–1 μm band and that an apparent broad bump around 3 μm might be dust emission. Neugebauer et al. (1987) obtained energy distributions from 0.3 to 2.2 μm for the complete set of quasars in the Palomar-Green (PG) survey (Green, Schmidt, & Liebert 1986) as well as some longer wavelength observations. A majority of objects could be fitted with two power laws ($\alpha \approx -1.4$ at lower frequencies, $\alpha \approx -0.2$ at higher frequencies) plus a "3000 Å bump."

Measurements at shorter and longer wavelengths were facilitated by the *International Ultraviolet Explorer* (*IUE*) and the *Infrared Astronomical Satellite* (*IRAS*), launched in 1978 and 1983, respectively. Combining such measurements with ground-based data, Edelson & Malkan (1986) studied the spectral energy distribution of AGN over the wavelength range 0.1–100 μm. The 3–5 μm "bump" was present in most Seyfert galaxies and QSOs, involving up to 40% of

the luminosity between 2.5 and 10 μm. All Sy 1 galaxies without large reddening appeared to require a hot thermal component, identified with the increasingly popular concept of emission from an accretion disk. Edelson & Malkan (1987) used *IRAS* observations to study the variability of AGN in the far-infrared. The high-polarization objects varied up to a factor 2 in a few months, but no variations greater than 15% were observed for "normal" quasars or Seyfert galaxies. The former group was consistent with a class of objects known as "blazars" that are dominated at all wavelengths by a variable, polarized nonthermal continuum. Blazars were found to be highly variable at all wavelengths, but most AGN appeared to be systematically less variable in the far-infrared than at higher frequencies. This supported the idea of thermal emission from dust in the infrared. This was further supported by observations at submillimeter wavelengths that showed a very steep decline in flux longward of the infrared peak at around 100 μm. For example, an upper limit on the flux from NGC 4151 at 438 μm (Edelson et al. 1988) was so far below the measured flux at 155 μm as to require a slope steeper than $\nu^{+2.5}$, the steepest that can be obtained from a self-absorbed synchrotron source without special geometries. Dust emission could explain a steeper slope because of the decreasing efficiency of emission toward longer wavelengths.

Sanders et al. (1989) presented measurements of 109 QSOs from 0.3 nm to 6 cm (10^{10}–10^{18} Hz). The gross shape of the energy distributions was quite similar for most objects, excepting the flat spectrum radio-loud objects such as 3C 273. This typical energy distribution could be fitted by a hot accretion disk at shorter wavelengths and heated dust at longer wavelengths. Warping of the disk at larger radii was invoked to give the needed amount of reprocessed radiation as a function of radius. As noted by Rees et al. (1969) and others, the rather steep slope in the infrared, giving rise to an apparent minimum in the flux around 1 μm, could be explained naturally by the fact that grains evaporate if heated to temperatures above about 1500 K. Sanders et al. saw "no convincing evidence for energetically significant nonthermal radiation" in the wavelength range 3 nm to 300 μm in the continua of radio-quiet and steep-spectrum radio-loud quasars. This paper marked the culmination of a gradual shift of sentiment from nonthermal to thermal explanations for the continuum of nonblazar AGN.

The blazar family comprised "BL Lac objects" and "optically violent variable" (OVV) QSOs. BL Lac objects, named after the prototype object earlier listed in catalogs of variable stars, had a nonthermal continuum but little or no line emission. OVVs have the emission lines of QSOs. These objects all show a continuum that is fairly well described as a power law extending from X-ray to infrared frequencies. They typically show rapid (sometimes day to day) variability and strong, variable polarization. The continuum in blazars is largely attributed to nonthermal processes (synchrotron emission and inverse Compton scattering). 3C 273 seems to be a borderline OVV (Impey, Malkan, & Tapia 1989). The need for relativistic motions, described above, arises in connection with this class of objects. A comprehensive study of the energy distributions of blazars from 10^8 to 10^{18} Hz was given by Impey & Neugebauer (1988). Bolometric luminosities ranged from 10^9 to $10^{14}\,L_\odot$, dominated by the 1–100 μm band. There was evidence for a thermal infrared component in many of the less luminous objects and an ultraviolet continuum bump associated with the presence of emission lines. When gamma rays are observed from AGN (e.g., Swanenburg et al. 1978), they appear to be associated with the beamed nonthermal continuum. The relationship of blazars to "normal" AGN is a key question in the effort to unify the diverse appearance of AGN.

IRAS revealed a large population of galaxies whose luminosity was strongly dominated by the far-infrared (Soifer, Houck, & Neugebauer 1987). (Rieke 1972 had found early indications of a class of ultraluminous infrared galaxies.) The infrared emission is thermal emission from dust, energized in many cases by star formation but in some cases by an AGN. One suggested scenario was that some event, possibly a galactic merger, injected large quantities of gas and dust into the nucleus. This fueled a luminous episode of accretion onto a black hole, at first enshrouded by the dusty gas, whose dissipation revealed the AGN at optical and and ultraviolet wavelengths (Sanders et al. 1988).

4.6. The Black Hole Paradigm

The intriguing paper by Lynden-Bell (1969) still did not launch a widespread effort to understand AGN in terms of accretion disks around black holes. Further impetus came from the discovery of black holes of stellar mass in our Galaxy. Among the objects discovered by *Uhuru* and other early X-ray experiments were sources involving binary star systems with a neutron star or black hole. "X-ray pulsars" emitted regular pulses of X-rays every few seconds as the neutron star turned on its axis. The X-ray power was essentially thermal emission from gas transferred from the companion star, impacting on the neutron star with sufficient velocity to produce high temperatures. Another class of source, exemplified by Cyg X-1, showed no periodic variations but a rapid flickering (Oda et al. 1971) indicating a very small size. Analysis of the orbit gave a mass too large to be a neutron star or white dwarf, and the implication was that the system contained a black hole (Webster & Murdin 1972; Tananbaum et al. 1972). The X-ray emission was attributed to gas from the companion O star heated to very high temperatures as it spiraled into the black hole by way of a disk (Thorne & Price 1975).

Galactic X-ray sources, along with cataclysmic variable stars, protostars, and AGN, stimulated efforts to develop the theory of accretion disks. In many cases, the disk was expected to be geometrically thin, and the structure in the vertical and radial directions could be analyzed separately. A key uncertainty was the mechanism by which angular momentum is transported outward as matter spirals inward. In a highly influential paper, Shakura & Sunyaev (1973) analyzed disks in terms of a dimensionless parameter α that characterized the stresses that led to angular momentum transport and local energy release. General relativistic corrections were added by Novikov & Thorne (1973). This "α-model" remains the standard approach to disk theory, and only recently have detailed mechanisms for dissipation begun to gain favor (Balbus & Hawley 1991). The α-model gave three radial zones characterized by the relative importance of radiation pressure, gas pressure, electron scattering, and absorption opacity. The power producing regions of AGN disks would fall in the "inner" zone dominated by radiation pressure and electron scattering. Electron scattering would dominate in the atmosphere as well as the interior and modify the local surface emission from an approximate blackbody spectrum. The "inner" disk zone suffers both thermal and viscous instabilities (Pringle 1976; Lightman & Eardley 1974), but the ultimate consequence of these was unclear. A model in which the ions and electrons had different, very high temperatures was proposed for Cyg X-1 by Eardley, Lightman, & Shapiro (1975). This led to models of "ion supported tori" for AGN (Rees et al. 1982). The related idea of "advection-dominated accretion disks" or "ADAFs" (Narayan & Yi 1994) recently has attracted attention.

A key question was, do expected physical processes in disks explain the phenomena observed in AGN? In broad terms, this involved producing the observed continuum and, at least in some objects, generating relativistic jets, presumably along the rotation axis. Shields (1978b) proposed that the flat blue continuum of 3C 273 was thermal emission from the surface of an accretion disk around a black hole. For a mass $\sim 10^9\ M_\odot$ and accretion rate $3\ M_\odot$ yr^{-1}, the size and temperature of the inner disk was consistent with the observed blue continuum. This component dominated an assumed nonthermal power law, which would explain the infrared upturn and the X-rays. Combining optical, infrared, and ultraviolet observations, Malkan (1983) successfully fitted the continua of a number of QSOs with accretion disk models. Czerny & Elvis (1987) suggested that the soft X-ray excess of some AGN could be the high-frequency tail of the thermal disk component or "big blue bump," which appeared to dominate the luminosity of some objects.

Problems confronted the simple picture of thermal emission from a disk radiating its locally produced energy. Correlated continuum variations at different wavelengths in the optical and ultraviolet were observed in the optical and ultraviolet on timescales shorter than the expected timescale for viscous or thermal processes to modify the surface temperature distribution in an AGN disk (e.g., Clavel, Wamsteker, & Glass 1989; Courvoisier & Clavel 1991). This suggested that reprocessing of X-rays incident on the disk made a substantial contribution to the optical and ultraviolet continuum (Collin-Souffrin 1991). Also troublesome was the low optical polarization observed in normal QSOs, typically 1% or less. The polarization generally is oriented parallel to the disk axis, when this can be inferred from jet structures (Stockman, Angel, & Miley 1979). Except for face on disks, electron scattering in disk atmospheres should produce strong polarization oriented perpendicular to the axis. Yet another problem was the prediction of strong Lyman edge absorption features, given effective temperatures similar to those of O stars (Kolykhalov & Sunyaev 1984). These issues remain under investigation today.

The question of fueling a black hole in a galactic nucleus has been difficult. Accretion rates of only a few solar masses a year suffice to power a luminous quasar, and even a billion solar masses is a small fraction of the mass of a QSO host galaxy. However, the specific angular momentum of gas orbiting a black hole at tens or hundreds of gravitational radii is tiny compared to that of gas moving with normal speeds even in the central regions of a galaxy. The angular momentum must be removed if the gas is to feed the black hole. Moreover, some galaxies with massive central black holes are not currently shining. Indeed, the rapid increase in the number of quasars with increasing look-back time (Schmidt 1972), implies that there are many dormant black holes in galactic nuclei. What caused some to blaze forth as QSOs while others are inert? A fascinating possibility was the tidal disruption of stars orbiting close to the black hole (Hills 1975). However, the rate at which new stars would have their orbits evolve into disruptive ones appeared to be too slow to maintain a QSO luminosity (Frank & Rees 1976). The probability of an AGN in a galaxy appeared to be enhanced if it was interacting with a nearby galaxy (Adams 1977; Dahari 1984), which suggested that tidal forces could induce gas to sink into the galactic nucleus. There, unknown processes might relieve it of its angular momentum and allow it to sink closer and closer to the black hole.

The growing acceptance of the black hole model resulted, not from any one compelling piece of evidence, but rather from the accumulation of observational and theoretical arguments suggestive of black holes and from the lack of viable alternatives (Rees 1984).

4.7. Unified Models

After the discovery of QSOs, the widely different appear-

ances of different AGN became appreciated. The question arose, what aspects of this diversity might result from the observer's location relative to the AGN? A basic division was between radio-loud and radio-quiet objects. Since the extended radio sources radiate fairly isotropically, their presence or absence could not be attributed to orientation. Furthermore, radio-loud objects seemed to be associated with elliptical galaxies, and radio-quiet AGN with spiral galaxies. The huge range of luminosities from Seyfert galaxies to QSOs clearly was largely intrinsic. However, some aspects could be a function of orientation. Blandford & Rees (1978) proposed that BL Lac objects were radio galaxies viewed down the axis of a relativistic jet. Relativistic beaming caused the nonthermal continuum to be very bright when so viewed, and the emission lines (emitted isotropically) would be weak in comparison. The same object, viewed from the side, would have normal emission-line equivalent widths, and the radio structure would be dominated by the extended lobes rather than the core.

A key breakthrough occurred as a result of advances in the techniques of spectropolarimetry. Rowan-Robinson (1977) had raised the possibility that the BLR of Seyfert 2 galaxies was obscured by dust, rather than being truly absent. Using a sensitive spectropolarimeter on the 120 inch Shane telescope at Lick Observatory, Antonucci & Miller (1985) found that the polarized flux of NGC 1068, the prototype Seyfert 2, had the appearance of a normal Seyfert 1 spectrum. This was interpreted in terms of a BLR and central continuum source obscured from direct view by an opaque, dusty torus. Electron scattering material above the nucleus near the axis of the torus scattered the nuclear light to the observer, polarizing it in the process. This allowed Seyfert 2 galaxies to have a detectable but unreddened continuum. However, the broad lines had escaped notice because the scattered light was feeble compared with the narrow lines from the NLR, which was outside the presumed obscuring torus. The same object, viewed face on, would be a Seyfert 1. Such a picture had also been proposed by Antonucci (1984) for the broad line radio galaxy 3C 234. Various forms of toroidal geometry had been anticipated by Osterbrock (1978) and others, and the idea received support from the discovery of "ionization cones" in the nuclei of some AGN (Pogge 1988). Orientation indicators were developed involving the ratio of the core and extended radio luminosities (Orr & Browne 1982; Wills & Browne 1986). The concepts of a beamed nonthermal continuum and an obscuring, equatorial torus remain fundamental to current efforts to unify AGN. Consideration of the obscuring torus supports the idea that the X-ray background is produced mostly by AGN (Setti & Woltjer 1989).

5. THE VIEW FROM HERE

The efforts described above led to many of the observational and theoretical underpinnings of our present understanding of AGN. The enormous effort devoted to AGN in recent years has led to many further discoveries and posed exciting challenges.

Massive international monitoring campaigns (Peterson 1993) have revealed ionization stratification with respect to radius in the BLR, that the BLR radius increases with luminosity, and that the gas is not predominantly in a state of radial flow inward or outward. This suggests the likelihood of orbiting material. Models involving a mix of gas with a wide range of densities and radii may give a natural explanation of AGN line ratios (Baldwin et al. 1995). Chemical abundances in QSOs have been analyzed in the context of galactic chemical evolution (Hamann & Ferland 1993). Recent theoretical work indicates that the observed, centrally peaked line profiles can be obtained from a wind leaving the surface of a Keplerian disk (Murray & Chiang 1997).

Efforts to understand the broad absorption lines (BALs) of QSOs have intensified in recent years. The geometry and acceleration mechanism are still unsettled, although disk winds may be involved here too (Murray et al. 1995). Partial coverage of the continuum source by the absorbing clouds complicates the effort to determine chemical abundances (e.g., Arav 1997).

The black hole model has gained support from indirect evidence for massive black holes in the center of the Milky Way and numerous nearby galaxies (see Rees 1998). This includes the remarkable "H_2O megamaser" VLBI measurements of the Seyfert galaxy NGC 4258 (Miyoshi et al. 1995), which give strong evidence for a black hole of mass $4 \times 10^7\ M_\odot$. X-ray observations suggest reflection of X-rays incident on an accretion disk (Pounds et al. 1989), and extremely broad Fe Kα emission lines may give a direct look at material orbiting close to the black hole (Tanaka et al. 1995). These results reinforce the black hole picture, but much remains to be done to understand the physical processes at work in AGN. In spite of much good work, the origin and fueling of the hole, the physics of the disk, and the jet production mechanism still are not well understood.

The nature of the AGN continuum remains unsettled; for example, the contribution of the disk to the optical and ultraviolet continuum is still debated (Koratkar & Blaes 1999). The primary X-ray emission mechanism and the precise role of thermal and nonthermal emission in the infrared remain unclear (Wilkes 1999). Blazars have proved to be strong γ-ray sources, with detections up to TeV energies (Punch et al. 1992).

Radio emission was key to the discovery of quasars, and radio techniques have seen great progress. The Very Large Array in New Mexico has produced strikingly detailed maps of radio sources, and shown the narrow channels of energy from the nucleus to the extended lobes. Maps of "head-tail" sources in clusters of galaxies shows the inter-

play between the active galaxy and its environment. The Very Long Baseline Array (VLBA) will yield improved measurements of structures on light-year scales in QSOs and provide insights into relativistic motions in AGN. Likewise, new orbiting X-ray observatories promise great advances in sensitivity and spectral resolution.

The Hubble Deep Field and other deep galaxy surveys have led to the measurement of redshifts for galaxies as high as those of QSOs. This is already stimulating increased efforts to understand the interplay between AGN and the formation and evolution of galaxies.

The decline of AGN as an active subject of research is nowhere in sight.

6. BIBLIOGRAPHY

In addition to the primary literature, I have drawn on a number of reviews, books, and personal communications. For the early work in radio astronomy, the books by Sullivan (1982, 1984) were informative and enjoyable; the former conveniently reproduces many of the classic papers. The book by Burbidge & Burbidge (1967) was an invaluable guide. A brief summary of early studies is contained in the introduction to Osterbrock's (1989) book. The "Conference on Seyfert Galaxies and Related Objects" (Pacholczyk & Weymann 1968) makes fascinating reading today. The status of AGN research in the late 1970s is indicated by the *Pittsburgh Conference on BL Lac Objects* (Wolfe 1978). Many aspects of AGN are discussed in the volume in honor of Professor Donald E. Osterbrock (Miller 1985), which remains of interest both from an historical and a modern perspective.

Review articles that especially influenced this work include those by Bregman (1990) on the continuum; Mushotzky, Done, & Pounds (1993) and Bradt, Ohashi, & Pounds (1992) on X-rays; and Stein & Soifer (1983) on dust in galaxies. Historical details of the discovery of QSO redshifts are given by Schmidt (1983, 1990); and an historical account of early AGN studies is given in the introduction to the volume by Robinson, Schild, & Schucking (1964). A comprehensive early review of AGN was given by Burbidge (1967b). A review of superluminal radio sources is given by Kellermann (1985), and the emission-line regions are reviewed by Osterbrock & Mathews (1986). A succinct review of important papers in the history of AGN research is given by Trimble (1992).

Recent books on AGN include those of Krolik (1999), Peterson (1997), and Robson (1996). Many interesting articles are contained in the volume edited by Arav et al. (1997). Recent technical reviews include those by Koratkar & Blaes (1999) on the disk continuum; Antonucci (1993) and Urry & Padovani (1995) on unified models; Lauroesch et al. (1996) on absorption lines and chemical evolution; Ulrich, Maraschi, & Urry (1997) on variability; and Hewett & Foltz (1994) on quasar surveys.

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