ACTIVE GALACTIC NUCLEI

In the eye of the beholder

C. Martin Gaskell

HOW similar are the different types of quasar activity? How far can they be unified? To what extent does our classification of an active galaxy merely depend on the angle at which we view it? These were some of the main questions addressed at a recent workshop, *Grand Unified Theories of Active Galactic Nuclei**, the word "theories" being carefully chosen because three main schemes were discussed.

The first, originally proposed by Blandford and Rees[1], is that so-called BL Lac objects (highly variable and highly polarized objects which lack obvious strong emission lines) are really low-power radio galaxies (of so-called Fanaroff–Riley class I, or FR I sources) whose relativistic radio jets are aimed at us like a searchlight. This unification scheme is now generally accepted, and is a necessary consequence of special relativity. Many extragalactic radio sources show apparent superluminal (faster than light) motion, which must be due to relativistic motion close to the line of sight. Relativistic motion produces very anisotropic emission ('relativistic beaming' along the direction of motion). Therefore, when the beam is aimed at us, its radiation dominates what we see. When it is not, the object seems much fainter.

Centaurus A

Blandford and Rees's explanation has now been shown to work well, quantitatively. Both the extended radio emission and the extended optical emission-line properties of BL Lacs match those of low-luminosity FR I radio galaxies. And the observed relative numbers of BL Lacs to FR I radio galaxies is that expected from the model. Interesting new evidence supporting the model is that the energetics of the emission-line gas in the direction of the radio jets in the nearby FR I radio galaxy Centaurus A require an X-ray flux about 200 times stronger than seen from the Earth (R. Fosbury, Space Telescope Science Institute). The flux the gas clouds see is in fact comparable to that of the prototypical BL Lac object, BL Lac, itself. If the Earth were in a different place, we might classify Cen A as a BL Lac object.

The relativistic beaming invoked in Blandford and Rees's model for BL Lacs is a case of intrinsic beaming, a property of the galaxy's central engine itself. In the second scheme, an attempt to unify Seyfert 1 and 2 galaxies, extrinsic beaming is required. Seyfert 1 galaxies show broad emission lines (due to photoionized gas with a density of 10^{10} cm^{-3} moving at speeds of up to a few per cent of the speed of light) whereas Seyfert 2s show only narrow emission lines (from slower-moving, lower-density gas). Keel[2] discovered that Seyfert 1 galaxies are preferentially orientated pole-on towards us (Seyfert 2s are not), but the idea that perhaps all Seyfert 2s are Seyfert 1s seen from the side, with dust obscuring the broad line region, was at first not generally accepted. Seyfert 2s are not strong sources of X-rays, unlike Seyfert 1s, and their radio structures were thought to be different. Also, the broad lines in a number of Seyfert 1s can disappear almost completely at times, making them look like Seyfert 2s.

The Seyfert unification scheme was strengthened, however, by the discovery[3] of the spectrum of a Seyfert 1 galaxy in the polarized light of the classic Seyfert 2 galaxy NGC1068. Apparently in NGC 1068 there is a physically thick nuclear torus blocking our direct view of this galaxy's nucleus, which we can detect only through light scattered off electrons above the disk or reflected off nearby dust clouds. That is, the thick torus causes extrinsic beaming.

Further polarization observations[4] have since revealed other Seyfert 2s with hidden broad lines, strengthening the case for unification. Furthermore, some of the earlier objections to the scheme have been discounted: new radio observations[5] have largely eliminated the systematic differences thought to exist between the galaxies' radio properties; and the X-ray spectra Seyfert 2s now turn out to be similar to those of Seyfert 1s. Where differences remain (as in the properties of narrow emission lines), the debate at the workshop centred on whether or not they can be explained in a unified theory by orientation effects and what the role of selection effects is in different samples.

Perhaps the most interesting new evidence to support extrinsic beaming was the observation[6] of gas in and around the host galaxies, showing that the nucleus lights these up only in cones aligned along the radio axis (see figure). The exact nature of the torus and its effect at various wavelengths have yet to be determined. S. Simkin (Michigan State University) presented evidence that the morphology of the spiral arms of the host galaxies differ between Seyfert 1s and 2s. If this cannot be explained away as some selection effect it supports the idea that there are differences between Seyfert 1 and 2 galaxies more fundamental than simple orientation.

The third unification scheme considered at the workshop is an extension of a proposal of Orr and Browne[7]. This is that there is a progression among the stronger extended radio sources (the so-called FR II sources): at one extreme, there are optically weak objects showing only narrow emission lines from low density gas (so-called narrow-line radio galaxies); then radio galaxies showing broad emission lines, and the optically brighter quasi-stellar objects (QSOs) with lobe-dominated radio emission; and finally QSOs with core-dominated radio emission. It is postulated that that sequence is explicable if the first extreme is an FR II source seen sideways on and the others have the radio jet progressively turned towards us. This scheme is a combination of the previous ones and invokes both intrinsic and extrinsic beaming. Although extensive evidence including new polarization observations (B. J. Wills, University of Texas) supports it, as with the Seyfert unification scheme, a few remaining problems raise doubts as to whether this is the whole story.

Bimodality

What differences cannot be explained by current unified theories? The main one everyone seemed to agree on is that between radio-loud and radio-quiet quasars. The most recent observations confirm that there is indeed a fundamental bimodality in the radio power of quasars. Also the difference between FR I and FR II radio sources cannot be explained in terms of orientation, and broad-absorption-line quasars refuse to fit into the schemes.

Of the other parameters needed in the unified quasar theories, the most obvious are the mass of the central black hole and, perhaps, the rate at which matter is accreted onto it. This accretion mechanism is generally accepted as being the basic source of luminosity in active galactic nuclei. S. Phinney (California Institute of Technology) noted that the most important relation for observers to produce is that between luminosity and mass. Progress in learning about the size, structure and kinematics of the broad-line region from variability studies is now making it possible to verify previous indirect estimates of the mass–luminosity relationship for quasars[8]; the results are consistent with accretion occuring at a relatively modest rate, a few per cent of the so-called Eddington rate (the maximum possible

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**Grand Unified Theories (GUTs) of Active Galactic Nuclei.* Space Telescope Science Institute, Baltimore, 25–27 July 1990.

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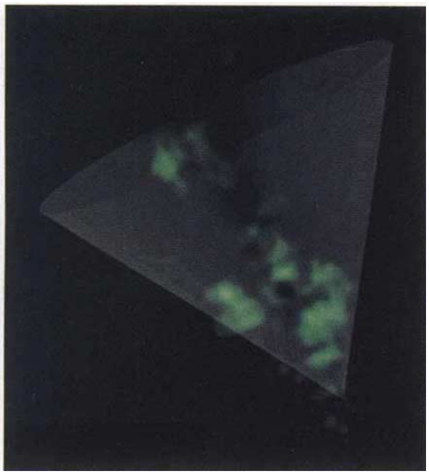

The core of the galaxy NGC1068 as recorded recently by the Faint Object Spectrograph on the Hubble Space Telescope. The image clearly shows small clouds of ionized gas illuminated by the conical extrinsic emission from the galaxy's nucleus. (The extent of the cone, aligned with the radio axis, is indicated by the artificial computer-generated graphic.)

rate for steady spherically symmetric accretion) over a range of black hole masses. Another factor to include is the quasar's environment: rather surprisingly, no one at the workshop mentioned the possible role of galaxy mergers.

What are the biggest remaining puzzles? Very fast X-ray variability is a severe difficulty for any model. About a third of the Seyferts looked at by EXOSAT vary on a timescale of hours; five varied significantly in only 20 minutes. Some ultrafast radio variability also seems to be intrinsic to the sources. The origin of the jets remains a problem. Accretion disks are frequently suggested to be the means of extracting the gravitational energy to power quasars (and are also a means of providing some of the collimation for beaming), but they present serious observational and theoretical problems. One is the lack of hydrogen bound–free edges in the spectra in either emission or absorption[9]: such edges are seen in the accretion disks that surround cataclysmic variable stars but not quasars. Other problems include the relativity low polarization of quasars and the uniformity of apparent temperature of the ultraviolet spectrum in different objects and in individual objects as they vary. So although the unified theories have come a long way, we are still far from having a single grand unified theory of quasars. ☐

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SOLID-STATE PHYSICS

Single-molecule probes

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UNDERSTANDING the nature of molecular dynamics in condensed phases has been a central theme in physics and chemistry for many years. On page 225 of this issue[1], Ambrose and Moerner report monitoring the fluorescence of single pentacene molecules in a molecular crystal of *p*-terphenyl. The fluorescence frequency of the pentacene molecule can jump by small amounts, the mean time between these jumps being 20–420 s. The authors interpret these frequency jumps as the result of changes in the local molecular environment of the pentacene molecule. Thus this experiment provides the first direct measurement of these local motions, and paves the way for detailed analyses of molecular dynamics in condensed phases.

The use of probe molecules that can be monitored spectroscopically is a time-honoured method for determining local structure and dynamics in condensed phases. One hopes, of course, that the probe molecule will not perturb the structure and dynamics of the host system to any significant extent. What one learns from the optical spectroscopy of dilute impurity probes in crystals and amorphous solids depends on the timescales involved. For times shorter than the fluorescence lifetime of the impurity, small-amplitude thermal motions of the host molecules occur that are statistically the same for each impurity. These motions rapidly vary the resonance frequency of the impurity, and thus produce what is known as homogeneous line broadening of the absorption or fluorescence spectrum[2,3]. On a timescale somewhat longer than the excited state lifetime, each impurity sees an average environment that is time independent and is different from the other impurities owing to disorder in the host crystal or glass. This produces inhomogeneous broadening. The actual absorption or fluorescence spectrum at low temperatures (1.5–10 K) is usually predominantly inhomogeneous. Nonetheless, various techniques — fluorescence line narrowing[4], hole burning[4], photon echo[4] and statistical fine structure[5] — have been developed that allow a determination of the homogeneous linewidth in these inhomogenously broadened systems.

On a timescale substantially longer than the excited state lifetime, the time-averaged host environment of any particular impurity may change significantly, leading to a change in the absorption or fluorescence frequency. The average of this process over all impurities is known as spectral diffusion, which is thought to account for the discrepancy between photon-echo dephasing times and hole widths from hole-burning experiments for resorufin in organic glasses[6] — the former experiments measure only short-time dynamics, whereas the hole widths also reflect a contribution from the longer-timescale spectral diffusion.

The direct observation of molecular dynamics from impurity spectroscopy[1] relies on the detection of single molecules, which has recently been achieved through double-modulation absorption[7] and fluorescence[8] techniques. The key to the detection of single molecules in crystals involves both the spatial and the spectral isolation of the impurities, achieved by using very thin crystals and small laser spots and by tuning the laser frequency significantly away from the central maximum of the absorption lineshape. The fluorescence technique allows one to see the frequency jumps of individual probe molecules.

These can provide much more information than the average spectral changes measured in more traditional experiments, such as hole burning, that involve many impurities. Thus one could measure distributions of jump times and frequency changes and the correlations between them, or, for example, the frequency–frequency time-correlation function for a single molecule. The temperature dependence of these quantities should enable one to determine, by comparing with theoretical models, the specific molecular motions of the host that are responsible for the frequency jumps.

One possible limitation of the technique is that only those impurity molecules way out in the wings of the inhomogeneous distribution, which by definition means those molecules in atypical environments, can be spectrally isolated. One would, of course, like to develop a technique that could measure the environmental changes in real time near typical impurities. Nonetheless, the detailed data that are sure to follow from the present generation of experiments will provide grist for the mill for quite some time. ☐

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