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Multiband Impressions of Active Galactic Nuclei

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Abstract. I summarize the activity of the workshop "Multiband Approach to AGN" held in Bonn, Germany from 30 September to 2 October 2004. I compare the state of knowledge of the field to what existed in the 1960s to demonstrate that we have indeed made progress. I highlight some impressive advances of our knowledge that I gleaned from the presentations at the workshop. I also list some embarrassing scandals where gaps in understanding still exist despite our often heroic attempts to describe accurately the physics of AGNs.

Key words. active galactic nuclei; multifrequency observations

1. Introduction

I started the written record of this workshop with the statement, "Active galactic nuclei (AGNs) are very complex physical systems." Indeed, they are, but with hundreds—perhaps thousands—of brilliant minds working on the problem, we would hope that we have made substantial progress toward solving the puzzles. After listening to the talks at the workshop, I conclude that indeed we have. However, AGNs continue to humble us by resisting our efforts to describe them as accurately as we would like.

In this summary, I review some of the highlights of the workshop. There were too many for me to include them all, so I focus on those that are relevant to the general points that I wish to make. I apologize to all those that I omit, and assure the authors and the reader that this does not imply that I consider them unworthy of inclusion. I also appeal to having been badly time-dilated by a hurricane-induced day-late arrival and consequent lack of sleep throughout the duration of the meeting.

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2. Some impressive advances in understanding

In our moments of discouragement when it seems that our ignorance exceeds our knowledge of AGNs, we need to remind ourselves of what we knew in the 1960s. Optically, quasars were still quasi-stellar, with their connection to galaxies an uncertain hypothesis rather than the current well-supported conclusion. Suggestions that extended radio lobes are fed by jets and that these jets are relativistic were in the realm of esoteric theory, yet to be evident in interferometric images that became prevalent in the latter 1970s. X-rays and γ-rays were thought to be emitted, but the instrumentation was too insensitive to detect anything beyond our vicinity of the universe. How primitive it now seems, except for the musings of British theorists (Rees, Lynden-Bell) who proposed that accretion onto black holes powered jets that propel converted gravitational po-

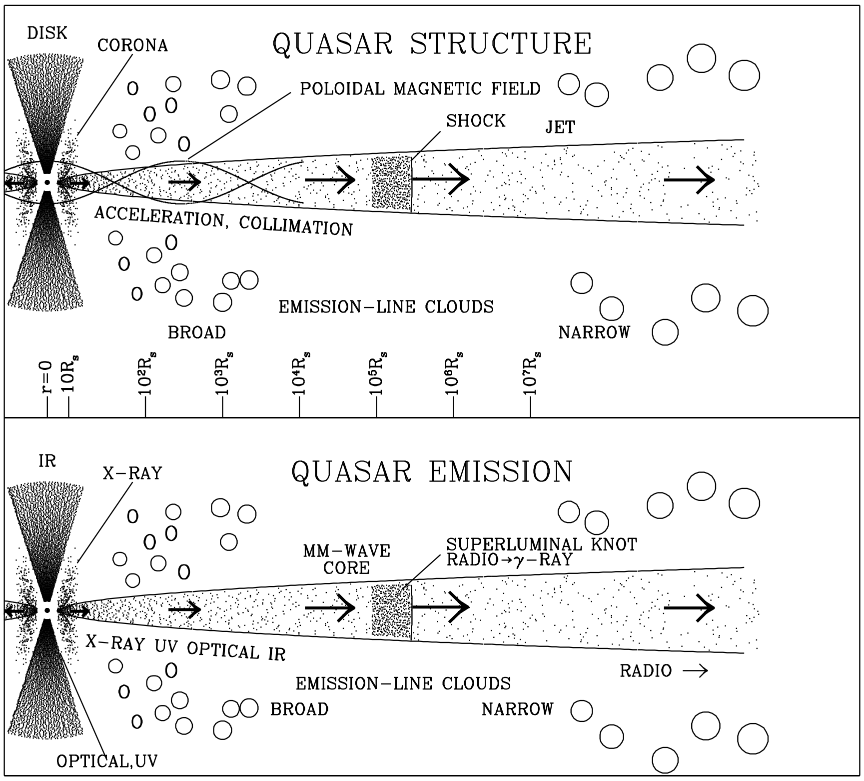

Fig. 1. Cartoon of the physical structure and emission regions of a radio-loud AGN, not including the extended radio lobe at the end of the jet.

tential energy into interstellar and intergalactic space in the form of relativistic flows of ultra-relativistic particles.

We now know enough to draw the cartoon of Figure 1, which I showed at the onset of the workshop. Although we may have some of the details wrong close to the black hole, and we are not sure about the kinematics of the emission-line (and absorption-line) clouds, we think that most of the picture is accurate. This is a great achievement, since everything inside the mm-wave core of the jet is unresolved on all our images.

While it would be possible to discuss every aspect of the sketch, I will instead concentrate on the progress revealed at the workshop—without references, since they correspond to the papers in this volume. I will proceed from the outside in.

- The host galaxies of quasars, whether radio-loud or -quiet, are giant elliptical galaxies. I suppose that this is a corollary of the nuclear black-hole mass $M_{\rm BH}$ being proportional to the velocity dispersion of stars in the spheroidal component of a galaxy. A quasar-class luminosity requires large $M_{\rm BH}$ and therefore implies the spheroidal component of a giant elliptical.

- IR/submm observations are revealing the properties of AGNs in the early universe. We find that there was already a high amount of dust at quite early epochs.
- High-redshift quasars can be imaged at X-ray energies on kiloparsec scales (with Chandra) and at radio frequencies on parsec scales (with VLBI). As we study more objects in this way, we will learn about the evolution of jets and other features through cosmic time. The FIRST survey is playing a major role in identifying sources and populations of interest. I was impressed by Bob Becker's statement that they can actually measure the properties of *undetected* FIRST sources!
- Extended jets of quasars and radio galaxies are surprisingly strong X-ray emitters. Analysis of the quasar data leads to the conclusion that the jets of luminous FR 2 sources remain highly relativistic out to scales of tens or hundreds of kiloparsecs.
- IR interferometry has progressed to the point that it can image parsec-scale structure in nearby AGNs. The geometry and temperature distribution of the hot dust that inhabits these regions can be explored with this technique.
- Millimeter-wave VLBI imaging with dense time coverage provides the information needed to sort out changes in both bulk Lorentz factor and angle to the line of sight.
- Multiwaveband monitoring is revealing where the variable X-ray and γ-ray emission occurs and the likely processes that produce it. Surprisingly, in blazars much ($\sim$ all?) of this radiation comes from near the mm-wave core.
- We have some understanding of how black-hole/accretion-disk systems make jets. On parsec scales, polarized-intensity VLBI images support the possibility of helical magnetic fields in jets, as called for by jet launching models. However, it is not clear from theory how far from the black hole the field geometry should remain intact.
- Combining VLBI imaging with monitoring of the X-ray continuum and Fe Kα emission line is providing clues on the coupling between the jet and the central engine.
- Jets may produce X-rays near the black hole in some (all?) X-ray binaries, the cousins of AGNs. Perhaps the same is true in Seyfert and radio galaxies.
- IR/X-ray flares in the Galactic Center are informing us on processes very close to the event horizon of a massive black hole.

The above list represents only a fraction of our accomplishments, yet is still quite impressive. Has the field matured so that most of us should move on to more challenging problems, such as γ-ray bursts? Of course not: we still have a lot of work to do before we confidently declare a basic understanding of the main processes in AGNs.

3. Scandals: gaps in our understanding

I fear that the successes discussed in the previous section may cause the young AGN researchers attending the workshop to consider the field to be on a firmer foundation than is really the case. This section counters that notion, and I hope that it instills a healthy amount of humility. Julian Krolik's (1999) comprehensive monograph *Active Galactic Nuclei* ends with a list of unsolved aspects of AGNs that is still mostly valid today. I supplement Julian's excellent summary with a list of AGN "scandals" that I culled from the workshop. This time the order is arbitrary.

- After many years of trying and many claims, we have yet to compile complete samples of quasars. Selection effects still reign supreme, even as the samples grow tremendously in size. As Bob Becker stressed, it is important to define the properties of the objects that a given sample omits, but this is far from trivial.
- 3D hydrodynamical simulations produce artificial jets that get destroyed when perturbed. Why does nature always have an

easier time controlling high-energy phenomena in practice than we have in theory?

- Jets can accelerate electrons to TeV energies hundreds of kiloparsecs from the nucleus, extending our embarrassingly poor understanding of acceleration processes to larger scales and higher energies. See the comment under the previous item.
- We still cling to single-zone, uniform emission models without light-travel delays even though we know better, because they are easier to compute than multi-zone, retarded-time calculations. Computers are fast enough now to put an end to this shoddy practice.
- We cannot discern between inner-jet and accretion-disk (including the corona) emission in microquasars and non-blazar AGNs. Furthermore, edges in X-ray spectra can be fit by either absorption or emission lines. In addition, while the low-luminosity radio/LINER galaxy NGC1052 has an Fe Kα X-ray emission line with a "relativistic" low-energy wing that is variable, the more powerful FR 1 galaxy 3C 120 does not. Resolution of these issues is crucial to our attempts to test models for accretion disks, advection-dominated accretion flows (ADAFs), and jet formation.
- In a related vein. . . Presentations at the workshop proposed that (1) X-rays previously thought to be emitted by the corona of the accretion disk might come instead from the inner jet, (2) the jet carries away a large fraction of the system's luminosity, (3) ADAFs may replace the innermost accretion disk, and (4) partial covering might explain the broadened X-ray iron line, including its "relativistic" wing. If all this is true, maybe we can dispense with the accretion disk and black hole altogether! Of course, this is over the edge, but these developments shake our confidence in the conclusions that the community has drawn over the past couple of decades.
- Microquasars have periodicities and well-defined states of emission, but it has proven extremely challenging to find AGN analogies to such orderly behavior. Yet both are thought to be accreting black-hole systems.
- Our own Galactic Center is on a hunger strike. Although this is not a scandal of our making, it seems a bit embarrassing to have such feeble radiative output from our local supermassive black hole.

Regarding the penultimate item on the scandal list, we need to be aware that accreting black-hole systems are probably not self-scaling. While the basic length scale—the gravitational radius—and the corresponding light-crossing time vary directly with mass, the cooling time scale does not. That is why we do not think that standard accretion disks radiate X-rays in AGNs as they do in X-ray binaries: the temperature of the inner disk in the former is not as hot as is the case for stellar-mass black holes. Another size scale—the size of the broad emission-line region $R_{\rm BELR}$—should scale as the square-root of the ultraviolet luminosity $L_{\rm uv}$. But if the dynamics of the cloud is connected to the gravitational force exerted by the black hole, we should expect a linear relationship. The data thus far suggest that nature compromises such that $R_{\rm BELR} \propto L_{\rm uv}^{0.7}$ (Kaspi et al. 2000). The same study finds that the mass of the black hole is proportional to the square-root of the luminosity. We would have expected a linear relationship under the thinking that, on average, all AGNs of a given type radiate at some fraction of their Eddington luminosities. If these results hold up, it is yet another scandal, caused either by those nasty observational selection effects or by some deviation from what we, in our naïvete, consider to be proper physical behavior.

Here is an exercise for students (which, as usual, means that I do not know how to solve the problem): determine how the size scale of a jet (e.g., its width at ten or 100 gravitational radii) should vary with the mass of the black hole and bolometric unbeamed luminosity. This is probably related to the strength of the magnetic field in the inner accretion disk, which in turn is probably related to the gas pressure in the disk. This is among the things we need to understand before we can figure out how to scale microquasars up to AGN sizes.

4. Conclusions

Certainly the observational data on AGNs are vastly richer and the theoretical models more sophisticated than they were a decade ago, let alone 35-40 years in the past. We know much more about AGNs than was even dreamed of in the early 1960s. So, although we remain confused, our confusion is at a much more sophisticated level than ever before!

Leading the charge up the hill of understanding are the various multi-waveband techniques discussed at the workshop. When combined with theoretical models and simulations, this is the most powerful way to explore the fascinating physical phenomena of the most exciting long-lived objects in the universe.

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