BLACK HOLES, JETS, AND ACCRETION DISKS

MITCHELL C. BEGELMAN
JILA, University of Colorado, Boulder,
CO 80309-0440, USA

The prevailing paradigm for the energetic phenomena in active galactic nuclei and X-ray binaries—linking black holes, relativistic jets, and accretion disks—has been greatly strengthened in last the last few years by a host of spectacular observational discoveries, plus a few theoretical developments. I briefly describe some of the most dramatic new results.

1 Introduction

The advertised title of my talk — AGNs, QSOs, and Jets — is flawed in two respects, which is why I have decided to change it. First, it is redundant. If anyone at the start of 1996 still worried that radio-quiet QSOs differ fundamentally from Seyfert nuclei, i.e., garden-variety AGNs, in more than distance and luminosity, then the HST/WFPC2 images of quasar host galaxies observed by Bahcall, Disney, and collaborators should have laid those qualms to rest. Second, the original title was not general enough. It is becoming increasingly difficult for a theorist to discuss the central engines of AGNs without focusing on the generic features that make them so interesting: the conjunction of black holes, accretion disks, and jets. We now know that the latter trio also occurs, in scaled-down form, in X-ray binary systems (XRBs). A few of the developments I want to speak about concern the latter, so I am reserving the right to switch between AGNs and XRBs at will.

2 Searching for Black Holes

What is new in the search for black holes is an explosion of promising new techniques for finding them. The three "classical" techniques — binary mass functions for XRBs, velocity dispersions of stars and rotation curves of both stars and gas in galactic nuclei — are becoming ever more refined, as they yield additional black-hole candidates. But the last couple of years has seen the appearance of at least four "new" techniques. Two of these — measurement of stellar proper motions in the Galactic Center, and Keplerian rotation traced by water masers — probe the region from about $10^3$ to more than $10^5$ Schwarzschild radii. While these new methods are greatly strengthening the case for massive dark objects, they are not testing the general relativistic description of black holes per se. But the other two methods — broad X-ray
to observe the maser activity would make these systems somewhat rare. If
the masers are pumped by X-rays emitted close to the accreting black hole,
as seems likely,\(^8\) then a warp is also necessary in order for the opaque disk
to receive enough incident radiation. But as we shall see (§ 4.1), a warp may
be the rule, not the exception, in accretion disks. Given these conditions, a
standard thin accretion disk with enough mass flow to power the X-rays can
account nicely for the scale and intensity of the maser emission.\(^9\)

Indeed, water maser emission has been detected from nearly 20 AGNs.
Although a simple kinematic signature may not be ubiquitous, at least one or
two sources besides NGC 4258 show evidence for a thin disk. Most recently,
the characteristic rotation curve of an annulus has been mapped out in the
nucleus of the archetypal type 2 Seyfert galaxy NGC 1068.\(^10,11\) The central
mass is about \(10^7 M_\odot\), implying that this luminous AGN is radiating at close
to its theoretical maximum, the Eddington limit.

### 2.3 Broad X-ray Lines

X-ray observations by the Japanese ASCA satellite may be providing the
first direct evidence for disk-like flow close to the event horizon of a black
hole.\(^12,13,14\) ASCA’s superior spectroscopic capability has revealed that the
iron Kα emission lines observed in some Seyfert 1 galaxies are extremely broad,
with Doppler widths (at zero intensity) as high as \(c/3\) in some cases. These
lines are thought to arise from fluorescence of relatively cool (\(\sim 10^6\) K or less),
optically thick gas exposed to hard X-rays produced in an optically thin corona.
If the fluorescing gas forms the inner part of an accretion disk orbiting a black
hole, then the line profile should typically display a relatively narrow blue wing
boosted in intensity by the radial Doppler shift, and a broad red wing shaped
by the combination of gravitational redshift and transverse Doppler shift. The
best studied case, MCG-6-30-15, shows exactly these features in its high-intensity
state. Its rapid variability\(^15\) indicates that the line is produced “close in.”

Could a fortuitous combination of effects unrelated to the presence of a
black hole conspire to produce the observed profiles? While it would be difficult
to rule this out, simple models fall far short of explaining the data.\(^13\) Yet the
discovery that the Kα line profile in MCG-6-30-15 is strongly correlated with
the X-ray continuum flux casts doubt on the simplest model fits to the profile.
In particular, the intense blue wing disappears while the red wing is enhanced
when MCG-6-30-15 drops into its low-intensity state.\(^15\) These changes might be
driven by changes in external illumination or ionization level of the accretion
disk, and they may indicate that the black hole is spinning rapidly. More
extragalactic radio sources continue to uncover new examples of both these effects, with apparent Lorentz factors approaching 30 or more in some cases. In the Galactic X-ray binaries GRO J1655-40 and GRS 1915+105, black-hole candidates which produce pairs of jets following outbursts, it has been possible to follow the evolution of both jets. Measured asymmetries in brightness, length, and speed are fully consistent with the kinematic effects expected from a symmetric pair of relativistic outflows.

3.1 Gamma-ray Blazars

New evidence for relativistic flow comes from high-energy gamma-rays and rapid radio variability. The EGRET instrument on board Compton Gamma-Ray Observatory has shown that blazars—a class of AGNs with highly variable, polarized emission and compact, one-sided radio jets—often appear most luminous at GeV photon energies. Two blazars have been found to vary rapidly at TeV energies, as well. Such energetic photons could not escape if they were produced too close to the black hole, or in any very compact region, since they would interact with the dense radiation field of lower-energy photons to produce electron–positron pairs. But the rapid variability of the gamma-rays suggests that they are produced in a confined space. The resolution of this paradox is almost certainly that the gamma-rays are produced in a jet flowing toward us with a Lorentz factor \( \Gamma \sim 10 \) or more. Light travel-time effects would compress the apparent variability timescale by a factor \( \sim \Gamma^{-2} \), making the rapid variability compatible with the requirements for photon escape.

The gamma-rays presumably are produced by electrons (or pairs) in the jet Compton scattering background, or “seed,” photons to higher energies. But it is not clear where these seed photons come from. One source is synchrotron photons produced in the jet itself (and believed to be responsible for the lower-energy radiation from blazars). Another is the ambient radiation which impinges on the jet either directly from the accretion disk or after reprocessing by a diffuse scattering medium or emission-line clouds. The relative importance of these two sources would vary from object to object, partly accounting for the observed wide range of spectral and temporal properties.

3.2 Intraday Radio Variability

The interpretation of Intraday Radio Variability (IDV), also a common feature of blazars, is less certain. Using the variability timescale to estimate a maximum source size, one obtains apparent radio brightness temperatures ranging up to \( 10^{17} \) K or more. If the radio emission mechanism is incoherent
dominated progress on accretion disks. For the first time, three-dimensional magnetohydrodynamic models of Keplerian shear flows are beginning to provide a physical basis for the $\alpha$-model of accretion disk viscosity.\textsuperscript{39,40,41} Renewed interest in the role of energy advection in accretion disks has led to improved models and new insights into accretion flows with low radiative efficiency.\textsuperscript{42,43,44}

4.1 Radiation-driven Warping and Precession

I will dwell briefly on a third development, Pringle's\textsuperscript{45} discovery that accretion disks are unstable to warping driven by radiation pressure from the central luminosity source. Hints that direct radiation pressure or gas pressure from an X-ray heated wind could maintain an existing warp had previously appeared in the literature,\textsuperscript{46,47,48} but Pringle was the first to demonstrate that disks with prograde warps (relative to the direction of rotation) are genuinely unstable at sufficiently large radii. The radial scale and growth time of the warp are compatible with thin accretion disk models for the maser disk in NGC 4258, which indeed has a mild warp.\textsuperscript{49} Numerical models for the nonlinear growth of the instability, taking into account shadowing, suggest that the warping can become extreme, with the inner part of the disk effectively flipping over.\textsuperscript{50} Radiation from the central source would then be confined to two cones with time-dependent opening angles, reminiscent of the "ionization cones" observed in Seyfert galaxies.\textsuperscript{50,51}

Given enough time, warped disks could attain a steady state characterized by uniform precession.\textsuperscript{49} Estimates of the precession timescale suggest that this may be the answer to the longstanding question of what causes the 164-day precession of the jets in SS 433\textsuperscript{52}, the 35-day X-ray period in Hercules X-1\textsuperscript{53}, and the precession thought to occur in many other X-ray binaries.\textsuperscript{54} In these complicated systems, however, precession will not be driven solely by radiation torques — quadrupole gravitational torques must contribute as well, and will also break the symmetry (present in the linear theory of radiation-driven warping) between retrograde and prograde precession.

5 Concluding Remarks

From the many examples mentioned in this paper, it should be clear that the study of black-hole phenomenology is galloping ahead. A unified paradigm of AGNs and Galactic black-hole candidates, with its basic components of black hole, jets, and accretion disk, is more robust than ever before. Yet, such discoveries as maser disks in AGNs and Pringle's warping instability should