LA-UR-97-**3609**

Approved for public release;
distribution is unlimited

Title: **Accretion onto Black Holes: the Power
Generating Mechanism**

Author(s): S. A. Colgate, T-6
J. G. Hills, T-6
W. A. Miller, T-6

Submitted to: DOE Office of Scientific and Technical Information

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

ACCRETION ONTO BLACK HOLES: THE POWER GENERATING MECHANISM

Stirling A. Colgate, Jack G. Hills, and Warner A. Miller*
Theoretical Division

Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The physical relationships among accretion disks, quasars, black holes, collimated radio sources and galactic dynamos previously had been only weakly related without explicit cause and effect. We have constructed a physical evolution from large, primordial density perturbations to "damped Lyman alpha clouds," to galaxy formation, to black holes, jets, and the galactic dynamo. We have derived the general relativistic distortions of radiation emitted from close to the black hole and thereby have a new observational test of the central engine. The physics of accretion disks, the astrophysical dynamo, and magnetic reconnection are the least understood physical phenomena in astrophysics. They are still less understood in the general relativity (GR) field close to the black hole. This lack of physical understanding frustrates a quantitative evaluation of observations that define the evolution from the early universe to star formation. We have made progress in this understanding.

Background and Research Objectives

A significant fraction of astronomy and theoretical astrophysics is concerned with quasars, active galactic nuclei, collimated radio sources, and by inference, accretion disks and magnetic fields. These objects are among the most distant and energetic phenomena in the universe. Because they are energetic, they can be observed at great distances. Because of the Hubble law, great distances imply a long time in the past. Thus they seem to mark the genesis of galaxies and the conditions in galaxies that allow stars to form, planets, and then life. The unspoken contract with astrophysics is to make reasonable and indeed inevitable from physics the sequence of events from as early in the universe as possible to life on this planet. For example the very large array (VLA) and very long baseline array (VLBA) radio observatories have expended well over half their effort in attempting to understand these extra galactic objects since their discovery well over 20 years ago. Similarly the large optical telescopes are devoted almost exclusively to the most distant

* Principal Investigator, E-mail: wam@lanl.gov

observable phenomena. Hence in attempting to understand and relate these extreme phenomena, we are attempting to synthesize a physical history of our universe.

Surprisingly the most obscure processes in the early evolution from density perturbations emerging from the early universe to galaxies is the redistribution of angular momentum. This redistribution takes place at each step in the sequence of events starting at a "damped Lyman alpha cloud" and evolving to a massive black hole, which powers a quasar. A "damped Lyman alpha cloud" is a massive cloud of gas of $\approx 10^{12} M_{\odot}$ ($M_{\odot}$ = solar mass) including dark matter, at large red shift, 3 to 6, or in the past by the same factors in units of the age of the universe. The density of the cloud is roughly twice that of the average and hence is the large initial perturbation that starts the "Jeans" collapse to a galaxy. (The growth of density perturbations from the early universe up to this point has been studied extensively within the Theoretical Astrophysics Group at Los Alamos.)

The name, "damped Lyman alpha cloud," is derived from the peculiar shape of the redshifted ultraviolet absorption lines as seen through the cloud by the light from a still more distant quasar. Regardless, such massive clouds have random rotation due to the nonlinear random perturbations occurring at the time of their formation. This random rotation is relative small, $\approx 5\%$ in units of the gravitational binding energy of the cloud. Although relatively small this represents a large specific angular momentum at the large radius, ≈ 300 kpc, or 10^{24} cm of the initial cloud. At this large radius the cloud is also very thin, $\approx 10^{-3}$ g cm $^{-2}$ so that radiation and hence heat can readily escape, but regardless of the escape of heat, the angular momentum is conserved unless a force torques either the cloud or an inner fraction of the cloud. Without such a torque, for example, if the cloud initially rotated as a unit, then at the radius where the specific angular momentum has the same value as at the Schwarzschild radius of a $10^8 M_{\odot}$ Kerr (rotating) black hole, then the mass of cloud inside this radius would be only $\approx 10 M_{\odot}$. Thus without transporting angular momentum from the inside to the outside, such a massive, $10^8 M_{\odot}$, black hole could not form from these initial massive cloud conditions.

Importance to LANL's Science and Technology Base (STB) and National R&D Needs

Each of the three areas in astrophysics identified in this project find their counterparts in almost every facet of science involved with (1) magnetic fields, (2) rotation, and (3) long range forces. This investigation pushes the limits of numerical investigation and computational modeling, as is often the case with astrophysically motivated research. These investigations could have substantial impact on such programs as hurricane modeling, fusion research, solar physics and energy storage, not to mention the unifying understanding one gains in astrophysics.

Scientific Approach and Accomplishments

We believe that we have identified a simple explanation of how the evolution of a self gravitating cloud forms a black hole. In Fig. 1 we suppose that the cloud collapses to a bar-like structure and that the bar breaks up into smaller bars. The smaller bars collapse further and rotate faster. The mass of the arms of the smaller bar then torques the larger mass at larger radius and an exchange of angular momentum takes place. This is sometimes described as bars within bars (Schlosman et al. 1989; Friedli 1996). If the following particular scaling of exchange of angular momenta, dJ , and residual mass, dm , is made such that $dJ/J \sim dm/m$, then the Keplerian velocity of the orbits of dm is a constant. This constant velocity, independent of radius, is what is observed for almost all galaxies and leads to what is called a flat rotation curve and the prediction of dark matter. Over a finite scale, $\approx \times 100$, recent particle simulations by Navarro result in this same distribution of angular momenta and velocities of the inner mass fractions. Hence we believe such a scaling law is universal and therefore naturally leads to the mass at which an accretion disk forms at the center of the galaxy of $\approx 10^8 M_{\odot}$, just what is needed to make the massive black hole. This depends upon a reasonable description of how an alpha viscosity accretion disk works.

We believe such a disk works when pressure forces from matter accumulating on the outer periphery cause an angular momentum redistribution in the disk that excites a large co-rotating vortex. This is what forms the red spot in Jupiter and we have extended this model to the disk. To show this phenomenon we are attempting to make a demonstration model, but more importantly initiate the smooth particle hydrodynamics (SPH) simulation calculations with our multiprocessor computer. Such a disk depends

upon pressure forces and hence must be thick enough to contain the radiation. This thickness, of roughly 100 g cm^{-2} , is to be compared with the thinness of the Lyman alpha cloud in the beginning of $10^{-3} \text{ g cm}^{-2}$. The evolution of the bar instability and the scaling law leads naturally to the correct mass of $10^8 M_\odot$ in the central disk at the required thickness for the alpha viscosity, just what is needed for the massive black hole. Once the alpha disk enhanced viscosity mechanism initiates, all the mass is accreted to the central black hole as compared to only a fraction in the tidal torquing or bar mechanism. We therefore think that this is the most likely fashion for the formation of the quasar black holes.

Such a disk should also make a dynamo sufficient to power the collimated radio jets as well as create the magnetic field of the whole galaxy. This magnetic field is important because it allows star formation to take place without invoking the gravitational bar instability, and hence, the bulk of the barionic matter of the galaxy can and does form stars. The mechanism of such a giant accretion disk dynamo is shown in Fig. 2. A small, 10^{-4} , mass fraction of stars forms during the tidal torquing phase of the collapse of the Lyman alpha cloud. These stars will have independent orbits around the central mass and so will continuously collide with the disk ($\approx 10^4$ times) before disruption. This process has been calculated (Zurek 1994) to explain the "broad emission lines" so characteristic and such a puzzle in the observations of quasars. Each collision makes a large plume of matter torn loose from the disk that will rise far above the disk. This plume in addition will entrain any toroidal magnetic flux embedded in the disk. The expanding plume increases its moment of inertia and so will rotate more slowly than the rotating frame of the disk. This relative rotation of the plume and the disk twists any entrained magnetic flux giving rise to the "alpha" effect in the alpha-omega dynamo. The omega deformation is the shear in the rotation rate of matter as a function of radius of a Keplerian disk.

This dynamo should make enough magnetic flux in the age of the disk, $\approx 10^8$ years, to fill the galaxy with the observed galactic field of $\approx 3 \times 10^{-6}$ gauss. The magnetic flux is redistributed within the disk by the alpha viscosity diffusion and externally in the galaxy by hydromagnetic instabilities and reconnection. Thus no primordial, early universe magnetic field is required to explain the galactic magnetic field. A galactic magnetic field is necessary to explain star formation, cosmic rays, and galactic radio emission. In addition this magnetic field is twisted into a helix that is observed as the collimated radio sources. These twisted flux tubes dissipate by reconnection producing, in situ, the relativistic electrons necessary to explain their radio emission, superluminal sources, radio lobes, and the

acceleration of the ultra high energy cosmic rays, $\approx 3 \times 10^{20}$ eV. (A demonstration experiment using liquid sodium has been designed and is currently under way in cooperation with New Institute of Mining and Technology.)

This picture of the formation of the black hole of the quasar and the dynamo depends critically upon the physics in the neighborhood of the black hole. Hence, the major fraction of our work has been concerned with the observations and theory that will be affected by general relativity. Black holes manifest themselves, in part, through emission of intense radiation from material associated with accretion processes. Currently, about a dozen black hole candidates are known within the Galaxy and many more supermassive black holes are believed to be in the nuclei of active galaxies. It is likely that most, if not all of these black holes, are spinning near their maximal allowable rate when the angular momentum J and mass M are related by $J \sim GM^2/c$. Thus light emitted from the region close to the horizon of a rotating black hole is subject to frame dragging.

To date, frame dragging has not been verified by any observation or measurement. However, there are currently two proposed satellite experiments, LAGEOS-3 and Gravity Probe-B, which are slated to measure this effect around the earth (Ciufolini 1986; Everitt 1976; Habib et al. 1994). While the frame dragging on satellite orbits around the earth is small (approximately 1 part in 10^7) when compared with the classical quadrupole contributions, in astrophysics the gravitational binding energies are large enough so as to make the dragging of inertial frames the dominant precessional effect. Furthermore, the frame dragging effect together with the shear viscosity of accreted material may be responsible for the alignment of an accretion disk with the parent black hole's spin axis, and may explain the stability of astrophysical jets (Bardeen and Peterson 1975). It is for these reasons that we search for an astrophysically relevant setting to observe frame dragging.

Toward this end, we explicitly compare integrated line profiles from a geometrically thin disk about a Schwarzschild and an extreme Kerr black hole and show that the line profile differences are small if the inner radius of the disk is near or above the Schwarzschild stable-orbit limit of radius $6 GM/c^2$. However, if the inner disk radius extends below this limit as is possible in the extreme Kerr spacetime, then differences can become significant, especially if the disk emissivity is stronger near the inner regions. We demonstrate that the first three moments of a line profile define a three-dimensional (3-D) space in which the presence of material at small radii becomes quantitatively evident in broad classes of disk models. In the context of the simple thin disk paradigm, this moment mapping scheme formally suggests that the iron line detected by the ASCA mission from

MCG-6-30-15 (Tanaka et al. 1995) is ~ 3 times more likely to originate from a disk about a rotating black hole than from a Schwarzschild system.

To obtain an image of an accretion disk as seen by a distant observer, we integrated the geodesic equations to obtain trajectories of photons which propagate from a uniform Cartesian grid of points in the sky plane to the accretion disk. The uniform grid may be associated with the field imaged by pixels of a charge-coupled device (CCD) detector.

An example of this procedure can be seen in Fig. 3, an image of a geometrically thin accretion disk around a maximally-rotating black hole ($a = M$). The inner and outer radii are at $1.25 R_g$ and $10 R_g$, respectively, and the disk is viewed at 75° with respect to the polar axis. The false colors indicate frequency shift of emitted photons as a result of Doppler and gravitational redshift. The image clearly shows the gravitational refocusing of the photons emitted from the far side of the disk; this effect causes the far side of the disk to appear wider as if it were bent toward the observer. The more subtle effects of frame dragging are evident in the overall shape of the disk and the asymmetry of frequency shift along contours of fixed radius between near and far sides of the disk.

We have presented results from a general purpose null-ray tracing code applied to the problem of emission from an accretion disk. Clearly, we can advance the level of modeling beyond the thin disk approximation. Thus as the resolution of observed x-ray line emission increases in the near future, we will be able to model more sophisticated physics to probe the environments of rotating black holes.

Publications

1. B. C. Bromley, K. Chen, and W. A. Miller, "Line Emission from an Accretion Disk Around a Rotating Black Hole: Toward a Measurement of Frame Dragging," accepted ApJ, Jan. 1997.
2. B. C. Bromley, K. Chen, and W. A. Miller, "Rotation of the Supermassive Black Hole in MCG-6-30-15," to be submitted to ApJ Lett. Dec. 1996.
3. S. Habib, D. Holz, A. Kheifets, R. A. Matzner, W. A. Miller, and B. W. Tolman, 1994, Phys. Rev. D **50**, 6068-6079.
4. W. H. Zurek, Siemiginowska, and S. A. Colgate, "Star-Disk Collisions and the Origin of the Broad Lines in Quasar," 1994, ApJ **434**, 46.
5. S. A. Colgate, "Acceleration in Astrophysics," 1994, Physica Scripta T **52**, 96-105.
6. S. A. Colgate, "The Coherent Acceleration of Ultra High Energy Cosmic Rays and The Galactic Dynamo," 1995, 24th Int. Conf. on CR, Rome, Italy, vol. 3, p. 341.

References

- [1] I. Schlosman, J. Frank, and M. C. Begelman, 1989, *Nature* **338**, 45.
- [2] D. Friedli, 1996, *Astron. Astrophys.* **312**, 761.
- [3] J. F. Navarro, C. S. Frenk, and S. D. M. White, *ApJ* **462**, 563-593.
- [4] J. M. Bardeen, and J. A. Peterson, 1975, *ApJ Lett.* **195**, L65
- [5] I. Ciufolini, 1986, *Phys. Rev. Lett.* **56**, 276.
- [6] C. W. F. Everitt, 1973, in *Experimental Gravitation*, B. Bertotti, Ed. (New York: Academic); R. A. VanPatten and C. W. F. Everitt, 1976, *Phys. Rev. Lett.* **36**, 629.
- [7] S. Habib, D. Holz, A. Kheyfets, R. A. Matzner, W. A. Miller, and B. W. Tolman, 1994, *Phys. Rev. D* **50**, 6068-6079.
- [8] V. Karas, D. Vokrouhlicky, and A. G. Polnarev, 1992, *MNRAS* **259**, 569.
- [9] A. Laor, 1991, *ApJ* **376**, 90.
- [10] C. W. Misner, K. S. Thorne, and J. A. Wheeler, 1970, *Gravitation* (San Francisco: W. H. Freeman & Co.).
- [11] Y. Tanaka, et al., 1995, *Nature* **352**, 659.
- [12] H. Thirring and J. Lense, 1918, *Phys. Z.* **19**, 156.
- [13] A. F. Zakharov, 1994, *MNRAS* **269**, 283.

Figure Captions

Fig. 1. The collapse of a Lyman alpha cloud of $\approx 10^{12} M_{\odot}$. It is subject to bar-like instabilities that both form the bars during collapse and cause the bars to break up into smaller bars. The smaller bars collapse further and rotate faster. The mass of the arms of the smaller bars then torque the larger mass at larger radius of the larger bars and an exchange of angular momentum takes place. The angular momenta scales such that $dJ/J \sim dm/m$. Then the Keplerian velocity of the orbits of dm is a constant. This constant velocity, independent of radius, is what is observed for almost all galaxies and leads to what is called a flat rotation curve and the prediction of dark matter. This scaling also leads to the mass at which an accretion disk forms at the center of the galaxy of $\approx 10^8 M_{\odot}$. This is what is needed to make the massive black hole.

Fig. 2. Stars which continuously collide with the alpha disk described above ($\approx 10^4$ times) before disruption. These collisions explain the "broad emission lines" observed from quasars. Each collision makes a large plume of matter torn loose from the disk that will rise far above (below) the disk. This plume in addition will entrain any toroidal magnetic flux embedded in the disk. The expanding plume increases its moment of inertia and so will rotate more slowly than the rotating frame of the disk. This relative rotation of the plume and the disk twists any entrained magnetic flux giving rise to the "alpha" effect in the alpha-omega dynamo. The omega deformation is the shear in the rotation rate of matter as a function of radius of a Keplerian disk. This dynamo should make enough magnetic flux in the age of the disk, $\approx 10^8$ years, to fill the galaxy with the observed galactic field of $\approx 3 \times 10^{-6}$ gauss.

Fig. 1 (see caption on p. 8)

Disk Dynamo

Fig. 2 (see caption on p. 8)

Fig. 3. The image of a geometrically thin and optically thick accretion disk around a maximally-rotating black hole of mass M . The inner radius and outer radius are at $1.25 M$ and $10 M$, respectively. This accretion disk is viewed at a 75° inclination. The false-gray-scale contour map indicates the ratio of observed frequency to emitted frequency: the dark, oval, shaded region at the top represents blue shift, and the bands around the radius indicate a red shift. The white (saturated) patch superimposed on the map contains the zero-frequency-shift contour.