SELF-CONSISTENT MODELS OF ACCRETION DISKS

GRANT NAG5-2837

ANNUAL PROGRESS REPORT NO. 3

FOR THE PERIOD 15 DECEMBER 1996 THROUGH 14 DECEMBER 1997

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December 1997

Prepared for
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

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The Smithsonian Astrophysical Observatory
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Annual Report for NASA Grant NAG 5-2837

for the Period 12/15/96 to 12/14/97

Publications

The following papers were completed during the period 12/15/96 to 12/14/97 under the support of the grant NAG 5-2837:

1. Lithium production in hot advection-dominated accretion flows in soft X-ray transients, Yi, I., & Narayan, R., 1997, ApJ, 486, 363

2. Advection-dominated accretion and black hole event horizons, Narayan, R., Garcia, M. R., & McClintock, J. E., 1997, ApJ, 478, L79

3. Advection-dominated accretion model of X-ray Nova Muscae in Outburst, Esin, A. A., McClintock, J. E. & Narayan, R., 1997, Proc. Texas Symposium in Relativistic Astrophysics, in press

4. Advection-dominated flows around black holes and the X-ray delay in the outburst of GRO J1655–40, Hameury, J.-M., Lasota, J.-P., McClintock, J. E., & Narayan, R., 1997, ApJ, 489, 234

5. Advection-dominated accretion and the spectral states of black hole X-ray binaries: Application to Nova Muscae 1991, Esin, A. A., McClintock, J. E., & Narayan, R., 1997, ApJ, 489, 865

6. Advection-dominated accretion model of Sagittarius A*: Evidence for a black hole at the Galactic Center, Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C., 1997, ApJ, in press

7. Spectral transitions in Cyg X-1 and other black hole X-ray binaries, Esin, A. A., Narayan, R., Cui, W., Grove, J. E., & Zhang, S.-N., 1997, ApJ, submitted

8. Advection Dominated Flows in the Kerr Metric: I. Basic Equations, Gammie, C.F., & Popham, R., 1997, ApJ, in press

9. Advection Dominated Accretion Flows in the Kerr Metric: II. Steady State Global Solutions, Gammie, C.F., & Popham, R., 1997, ApJ, submitted

10. Photon Bubbles in Accretion Disks, Gammie, C.F., 1997, MNRAS, submitted

11. On the Origin of Episodic Accretion in Dwarf Novae, Gammie, C.F., & Menou, K., 1997, ApJL, in press

In addition, several papers listed as "submitted" or "in press" in the previous Annual Report have now appeared in print:

Mechanisms for the outbursts of soft X-ray transients, Lasota, J. P., Narayan, R., & Yi, I., 1996, A&A, 314, 813

Advection-dominated accretion model of the black hole V404 Cyg in quiescence, Narayan, R., Barret, D., & McClintock, J. E., 1997, ApJ, 482, 448

Advection-dominated accretion flows: optically thin solutions, Narayan, R, 1996, in Basic Physics of Accretion Disks, eds. S. Kato, S. Inagaki, S. Mineshige, & J. Fukue, Gordon & Breach, p15

Advective disks, Narayan, R., 1997, in Proc. IAU Colloq. 163 on Accretion Phenomena & Related Outflows, A.S.P. Conference Series, eds. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario, p75

Models of quiescent black hole and neutron star soft X-ray transients, Yi, I., Narayan, R., Barret, D. & McClintock, J. E., 1996, A&A Suppl., 120, 187

Spectra and line profiles of FU Orionis objects: comparisons between boundary layer models and observations, Popham, R., Kenyon, S., Hartmann, L., & Narayan, R., 1996, ApJ, 473, 422

Heating of a star by disk accretion, Popham, R., 1997, ApJ, 478, 734

Boundary layers in cataclysmic variables and pre-main-sequence stars, Popham, R., 1997, in Proc. IAU Colloq. 163 on Accretion Phenomena & Related Outflows, A.S.P. Conference Series, eds. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario, p230

Nonlinear outcome of gravitational instability in optically thick disks, Gammie, C. F., 1997, in Proc. IAU Colloq. 163 on Accretion Phenomena & Related Outflows, A.S.P. Conference Series, eds. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario, p704

Description of Research

The PI, Dr. Ramesh Narayan, continued his investigations of advection-dominated accretion flows (ADAFs), with emphasis on applications to X-ray binaries containing black holes and neutron stars. This work, which has gone on for several years with the support of this grant, is now being recognized as the standard paradigm for understanding the various spectral states of black hole X-ray Binaries (BHXBs).

Paper 1 in the above list discusses an interesting problem in BHXBs, namely that several of these binaries have unusually large concentrations of lithium in their companion stars. This is puzzling because the lithium should have been destroyed in such old systems. We showed that, during quiescence, these BHXBs are likely to produce large quantities of lithium through spallation in the hot ADAF. Some of this lithium might reach the companion stars through an outflow.

Paper 2 describes a novel test to show that black holes have event horizons. We considered the class of soft X-ray transients and divided them into neutron star and black hole systems. We then calculated the ratio of the maximum to minimum luminosities, L_{max}/L_{min}, of these systems. According to the ADAF model, in quiescence, most of the

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energy released in accretion is advected with the flow and carried to the center. If the object in the center is a neutron star the energy will be radiated from the stellar surface. However, if it is a black hole the energy will disappear through the event horizon and L_{min} will be much less. We found quite convincing evidence that L_{max}/L_{min} is larger in black hole systems compared to neutron star systems. This provides proof that black holes really do have event horizons, a rather important result.

Paper 4 discusses the application of the ADAF model to the puzzling X-ray delay in the recent outburst of the BHXB, GRO J1655−40. Once again the ADAF model gives a beautiful explanation for the effect. According to this model, in quiescence, the system has a large ADAF zone in the center and the thin disk is restricted to large radii. When the thermal instability that causes the outburst begins in the outer disk, the optical flux goes up immediately. However, it takes several days for the disk to work its way into the ADAF zone. This causes the X-ray emission to be delayed. Without the hole in the center the X-ray delay would be much smaller and the observations cannot be explained.

Papers 3 and 5 give a fairly complete description of the various spectral states in BHXBs. This comprehensive work, along with paper 7 on Cyg X−1 and other BHXBs, will form a substantial part of the Ph.D. thesis of the PI's student Ann Esin. She is expected to graduate in fall 1998. In this work, Esin combined the ADAF model and the thin disk model in a very interesting way and showed that she can explain the quiescent state, the low state, the intermediate state, and the high state observed in these systems. She then applied the model to the outburst light curves of Nova Muscae 1991, and found that the model gives a very satisfying explanation. In paper 7, Esin applied the same model to three other BHXBs, Cyg X−1, GRO J0422+32 and GRO J1719−24. Once again, the model does a very good job of explaining the observations.

Paper 6 describes the application of the ADAF model to the famous supermassive black hole at the center of our Galaxy, Sgr A*. This source has been very difficult to understand for many years. The problem is that it is extremely underluminous and it has a very odd-looking spectrum. We showed that the ADAF model gives a nice explanation of all the observations. In particular, the low luminosity is natural in this model since most of the energy is advected to the center and lost into the black hole. In fact, the success of the model confirms that Sgr A* has an event horizon and therefore that it is a true black hole. This work complements the work on event horizons in BHXBs described in paper 2.

Dr. Charles Gammie and Dr. Robert Popham, two postdocs working with the PI, received partial support from the grant during the year under review and completed several papers.

Paper 8 writes down and solves equations describing steady-state, optically thin, advection-dominated accretion onto a Kerr black hole. The mean flow, described by the relativistic fluid equations, is axisymmetric and vertically averaged. The effects of turbulence are represented by a viscous shear stress. Unlike earlier treatments, this paper uses a causal prescription for the shear stress, does not assume the relativistic enthalpy is unity, and uses a relativistic equation of state. In the followup paper 9, the authors survey the parameter space for the numerical solutions found in paper 8. They find that

the temperature and density of the gas in the inner parts of the flow depends strongly on the black hole spin parameter a. The rate of angular momentum accretion is also shown to depend on a; for a greater than an equilibrium spin parameter a_{eq} the black hole is spun-down by the accretion flow. This paper also investigates the dependence of the flow on the angular momentum transport efficiency α, the advected fraction of the dissipated energy f, and the adiabatic index γ. For low values of α and f the inner part of the flow exhibits a pressure maximum and appears similar to equilibrium thick disk solutions.

Paper 10 shows that radiation dominated accretion disks are likely to suffer from a "photon bubble" instability similar to that described by Arons in the context of accretion onto neutron star polar caps. The instability requires a magnetic field of order thermal strength for its existence, and has a growth rate similar to that of classical Rayleigh-Taylor instability. In the nonlinear outcome the instability leads to enhanced vertical energy transport. Under some circumstances this may prevent the disk from becoming radiation dominated, and may thus explain what happens to a thin disk that is unstable by the famous Lightman-Eardley instability.

Paper 11 shows that dwarf nova disks in quiescence have rather low magnetic Reynolds number, of order 10^3. Numerical simulations of magnetized accretion disks suggest that under these conditions magnetohydrodynamic turbulence and the associated angular momentum transport is sharply reduced. The paper argues that this could be the physical origin of episodic accretion in dwarf nova disks. If so, the standard disk instability model needs to be revised.