A&A 500, 53–54 (2009)
DOI: 10.1051/0004-6361/200912147

Astronomy
&
Astrophysics
Special issue

COMMENTARY ON: SHAKURA N. I. AND SUNYAEV R. A., 1973, A&A, 24, 337

Accretion: the gold mine opens

A. King

Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH, UK
e-mail: ark@astro.le.ac.uk

In the early 1970s, Yakov Zeldovich suggested that two young Moscow astronomers, Nikolai Shakura and Rashid Sunyaev, should combine their efforts to understand how accretion could power bright X-ray sources.

The result was a paper now amongst the most cited in all astronomy. Another highly influential paper on accretion disks (Pringle 1981) calls it "seminal", and so it is. Yet it is not by any means the first paper on disks. The references in the paper make it clear that the authors knew of a large literature on the subject going back to the early 1960s. Indeed Pringle (1981) shows that knowledge of the principles and even the equations of disk theory dates back still earlier (to the 1920s and 1940s, respectively).

The reason for the paper's vast and deserved success lies partly in its approach to the problem it attacked, and partly in a technical innovation. Shakura and Sunyaev's title: "Black Holes in Binary Systems. Observational Appearance" makes their aim very clear. By the early 1970s the identification of pulsars as rotating neutron stars had encouraged astronomers to take the possible existence of black holes seriously, although it was still quite common to surround the term with inverted commas. (A modern hangover from this odd form of astronomical prudishness is the phrase "black hole candidate" still used by the fastidious, although I have yet to read of a "supermassive black hole candidate").

Several authors, notably Salpeter and Zeldovich, had already pointed out the efficiency of what we would now call accretion on to these objects. This made them plausible as engines driving extreme sources such as quasars, and Lynden-Bell (1969) had given the first modern picture of this process for galactic nuclei. The sudden rise of X-ray astronomy, particularly the early UHURU discoveries, gave a major impetus to this field.

The mere requirement that an object should produce X-rays at all was already challenging. It showed unambiguously that the accretion flow must itself be luminous, and so quite different from the cool protosolar disks studied in detail in the past. In addition, tight constraints on sizes, geometry, and timescales flowed from the identification of many of the early sources as close binaries. This opened the possibility of showing that accretion on to a black hole or a neutron star was the only reasonable way of explaining a mass of data. The challenge for theorists was to supply a robust theory of these accretion flows that was easy to apply to observations.

Several groups attempted this. The main difficulty was one that is still not completely removed, namely the nature of the process – usually called "viscosity" – which removes angular momentum and so drives accretion, thus tapping the gravitational energy of infall. There is a direct connection between viscosity and accretion rate, and in a steady disk one can infer the surface dissipation rate purely in terms of the latter. Observations made it clear that none of the obvious candidate mechanisms – certainly not the standard "molecular" viscosity for example – was adequate to drive accretion at the rates required.

Authors therefore resorted to various parametrizations of the unknown process, usually thought of as some kind of turbulent effect. Shakura and Sunyaev adopted the now famous alpha-prescription, in modern notation usually written

$$\nu = \alpha c_{\rm s} H.$$

Here ν is the kinematic viscosity, $c_{\rm s}$ the sound speed, and H the local disk scaleheight, i.e. the disk semithickness.

It is remarkable that such a simple parametrization allowed such far-reaching insights. It is an appealing choice. A (kinematic) "viscosity" is dimensionally a product of a lengthscale and a velocity, and one can think of these as describing random motions around the fluid's mean streaming velocity. If the random motions are roughly isotropic, their typical lengthscales cannot exceed H, while one might expect that supersonic random motions would dissipate rapidly through shocks. Thus one might hope that $\alpha < 1$.

Of course in reality a viscous process is described by a tensor, not a single number, and moreover even this number must in general vary with position and conceivably with time. However, in a disk where radiative cooling is able to remove the locally dissipated energy efficiently (a thin disk), α is well-defined, and this prescription gave a clean algebraic separation of radial and vertical structure. This was hugely significant, as it allowed clear descriptions of the physics of various regions of the disk. The authors found that radiation pressure was frequently dominant in the innermost regions around stellar-mass and (particularly) supermassive black holes and that the main opacity source was electron scattering, conditions that reminded them of those in the early Universe. They quickly realized that there was no reason that the outer disk boundary would know about the Eddington limit, so that supercritical accretion should exist. In Rashid Sunyaev's words:

> *"We were young, enthusiastic and had no doubts that we were developing a gold mine. Every day and every night (I was working at that time till 3–4 a.m.) brought something unexpected and very interesting".*

Article published by EDP Sciences

Their work offered a simple demonstration that the assumptions of Keplerian rotation, a thin disk, and efficient cooling were precisely equivalent. Miraculously, α appeared only with low powers in the theory, suggesting that the broad picture of these thin disks ($H/R \ll 1$) might survive future insights into the nature of viscosity. This weak dependence of the theory on its unknown parameter opened it to observational tests. Accordingly, observers began to look seriously at its predictions of spectra, luminosities, variability, and so on. More than 35 years on, it is clear that the picture has survived remarkably well. It is the basis of almost all discussions of accretion in close binaries, most in active galactic nuclei, and has been applied widely elsewhere. Accretion disk theory has achieved a resilience rather like stellar structure in the 1920s, before nuclear burning was fully understood. Just as then, we can get somewhere, even though we do not fully know the process generating the energy.

The authors' prescience is clear from the number of issues they touch on that remain areas of active investigation. For example, Shakura and Sunyaev already mention that magnetic fields might be involved in transporting angular momentum. We now know (Balbus & Hawley 1991) that the probable cause is the magnetorotational instability (one of its original discoverers in the plasma context being the 22-year-old Evgeny Velikhov). This field is still lively: observations are unequivocal in suggesting a value of α of order 0.1–0.4 in thin, ionized disks (where it is well defined), while current simulations give values about a factor 10 smaller, and in some cases resolution-dependent (cf. King et al. 2007).

Shakura and Sunyaev put considerable effort into discussing super-Eddington accretion, concluding that such disks would expel most of the excess mass flow, and have a luminosity logarithmically exceeding the formal Eddington value. Recently Begelman et al. (2006) and Poutanen et al. (2007) have shown that this picture is in excellent agreement with observations of the extreme accreting binary system SS433, and probably forms the basis for understanding the ultraluminous X-ray sources (ULXs).

The original paper also treats the problem of irradiation of the outer parts of the disk by the hard radiation from the central regions. The full significance of this work was not realized until much later, for disk stability (transient versus persistent X-ray sources: van Paradijs 1996; King et al. 1996), for direct observations (King & Ritter 1998), and for disk warping (Petterson 1977; Pringle 1996).

One could add to these examples. The paper is still stimulating research, as it has been right from its publication. Its first appearance in public, at IAU Symposium 55 in Madrid, 1972, was already an example of international collaboration. Its authors were not able to travel to Madrid. Their paper was read to the meeting by Jim Pringle.

Acknowledgements. I am grateful to Nikolai Shakura and Rashid Sunyaev for their comments, and to Jim Pringle for discussions over many years. I thank the Sterrewacht Leiden for warm hospitality, and Yuri Levin for comments.

References

Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Begelman, M., King, A. R., & Pringle, J. E. 2006, MNRAS, 370, 399
King, A. R., & Ritter, H. 1998, MNRAS, 293, L42
King, A. R., Kolb, U., & Burderi, L. 1996, ApJ, 464, L127
King, A. R., Pringle, J. E., & Livio, M. 2007, MNRAS 376, 1740
Lynden-Bell, D. 1969, Nature, 223, 690
Petterson, J. A. 1977, ApJ, 216, 827
Poutanen, J., Lipunova, G., Fabrika, S., Butkevich, A. G., & Abolmasov, P. 2007, MNRAS, 377, 1187
Pringle, J. E. 1981, ARA&A, 19, 137
Pringle, J. E. 1996, MNRAS, 281, 357
van Paradijs, J. 1996, ApJ, 464, L139
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337