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The Physics of Accretion onto Black Holes

Maurizio Falanga · Tomaso Belloni
Piergiorgio Casella · Marat Gilfanov
Peter Jonker · Andrew King *Editors*

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Cover illustration: Artist impression of an accreting black hole by H. Flinterman (Studio WW15) & SRON, Netherlands Institute for Space Research.

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Foreword

Maurizio Falanga · Luigi Stella

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Black holes were predicted long before the beginning of the space age; they were perceived as by-products of mathematical theories, existed only in the imagination of a few scientists. The idea of "dark stars" (they were dubbed "black holes" only in 1968) can be traced back to the late 18th century, when John Michell (English philosopher and geologist) and some years later to Pierre-Simon Laplace (French mathematician and astronomer) speculated that, if a planet or a star were dense enough, their escape velocity would equal the speed of light. Light particles (photons) leaving the surface of such a world, would rise, stop, and then fall back down like projectiles do. This "Newtonian" view of black holes, while conceptually interesting, is not an adequate description of what happens to light near a massive dense body.

By the end of the 19th century strong evidence had been found that the speed of light is a universal constant, which remains the same in any reference frame. By exploiting the constancy of the speed of light and the principle of relativity (stating that the laws of physics should remain the same in any *inertial* reference frame) in application to Maxwell's equations of electromagnetism, Albert Einstein developed in 1905 a new theory (the Theory of Special Relativity) that led to a deep revision of the concepts of space and time: contrary to simple intuition, space and time intervals do not remain unchanged for observers in motion with respect to one another.

After a decade of attempts, Einstein succeeded in formulating a theory gravity (and electromagnetism) obeying the general principle of Relativity, i.e. that physical laws are the same in *all* reference frames (inertial or non-inertial). Einstein's basic concept was to drop Newton's idea of a force (the gravitational force) that is responsible for the attraction of masses. In place of that he was guided by of what he defined the "happiest thought of his life": that the effects of gravity are cancelled in a body that accelerates because it falls

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freely, no matter what the body is. Stated differently, acceleration can mimic gravity and, vice-versa, gravity can mimic acceleration: that is the "Equivalence principle". By using the mathematical instrument of differential geometry, Einstein formulated a new theory, the Theory of General Relativity, in which gravitation and motion of both matter and light result from the geometric properties of space-time (rather than Newton's attraction force). In turn the geometry of space-time, the matter and light in particular, determine its varying curvature.

Some solutions of Einstein's equations of General Relativity predict that a sufficiently compact mass will curve space-time such much that nothing, not even light, can escape from inside a critical surface, the so-called event horizon: that provided the modern foundation of the black hole concept. According to the so-called "No Hair Theorem" stationary black holes are completely characterized by only three observables: mass, angular momentum and electric charge (the latter being irrelevant in astrophysical black holes). All other information (for which "hair" is a metaphor) about the matter which formed the black hole (or fell into it after formation) is lost behind the event horizon, and remains permanently inaccessible to external observers.

Since the early seventies, a wealth of observational evidence has been found for the presence of black holes in the universe. While nothing can escape from the event horizon, the regions in its immediate surroundings (that is, say, tens of times the horizon radius) can become very luminous and launch jets at speeds close to the speed of light. This happens when matter flows towards the black hole and releases up $\sim$40 % of its rest mass energy in the process. This "accretion" energy, might be supplemented by the extraction of part of the black hole's rotational energy.

Stellar mass black holes (4–15 solar masses) in binary systems are being discovered in increasing numbers in the Milky Way and nearby galaxies. Super-massive black holes, from millions to billion solar masses, exist in the centre of most if not all galaxies; the radiation they release when they are active deeply influences the evolution of their hosts. Though relatively quiescent, the $\sim$4 million solar mass black hole in the centre of our Milky Way is one of the best studied and offers very good prospects for direct imaging of the "shadow" caused by light bending in the vicinity of the event horizon.

Black holes are ideal laboratories for studying both physical properties of accretion onto compact objects and probing the effects of General Relativity in the strong field regime. These extreme phenomena are inaccessible to laboratory experiments. Through observations at high energies (mainly in the X-rays) and multiwavelength programs spanning the widest range of the electromagnetic spectrum, from the radio to TeV energies), our knowledge of astrophysical black holes has advanced considerably over the last two decades. Diagnostics have emerged which can directly probe the dynamics of matter motion very close to the black hole, where the strong field general relativistic effects become important. At the same time, considerable progress has been made developing advanced models and understanding the physics of accretion onto compact objects. Yet, a number of key issues remain poorly understood. For instance the interpretation and decomposition of the energy spectra of accreting black holes are still much debated. Similarly, different competing models are being investigated which explain at least part of the variability properties of black.

This book is presents a collection of reviews of astrophysical black hole. The first section of the contains very valuable introductory material about the history of the first observed black hole. The second section describes the physical models for the accretion flow around black holes of all masses, where the third and fourth sections describe the accretion on black holes from stellar mass to supermassive and its fundamental parameters. The fifth section is devoted to the accretion-jet interplay, while the last section reports an overview and outlook of black hole research.

It is our honour to warmly compliment the conveners and organizers of the Workshop; they conducted the whole workshop with great enthusiasm and dedication. We thank all those who participated in the workshop it is them who made it successful. This excellent book represents also an important outcome of the workshop: congratulations to all.

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Searching for Black Holes in Space

The Key Role of X-Ray Observations

Ken Pounds

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Abstract Although General Relativity had provided the physical basis of black holes, evidence for their existence had to await the Space Era when X-ray observations first directed the attention of astronomers to the unusual binary stars Cygnus X-1 and A0620-00. Subsequently, a number of faint Ariel 5 and Uhuru X-ray sources, mainly at high Galactic latitude, were found to lie close to bright Seyfert galaxies, suggesting the nuclear activity in AGN might also be driven by accretion in the strong gravity of a black hole. Detection of rapid X-ray variability with EXOSAT later confirmed that the accreting object in an AGN is almost certainly a supermassive black hole.

Keywords Black holes · X-ray astronomy · Uhuru · Ariel 5 · EXOSAT · GINGA

1 Introduction

The first recorded suggestion that there may be stars too massive for light to escape from their surface appears to have been made in 1783 by John Michell (McCormack 1968; Hockey 2007), a rector working at a church near Leeds in Yorkshire. Michell, who had studied geology at Cambridge, but chose a better-remunerated position in the church, also proposed that binary stars must have a common origin (rather than by chance encounter) and hence seems a worthy first reference in this historical review. However, a physical basis for the implied 'light bending' had to await developments in general relativity by Einstein and Schwarzschild more than a century later.

A key to the subsequent discovery of black holes, a term proposed by John Wheeler in 1965, is the extremely small (Schwarzschild) radius of the event horizon, with a correspondingly large potential energy release from accreting matter prior to falling into the hole. A further consequence of the small emission region is that the radiation temperature will be high, indicating that much of the luminosity will lie in the far UV or X-ray wavebands.

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Such simple considerations make it clear, with hindsight, why the first evidence that black holes actually exist had to await the Space Era, when the first opportunity arose to send X-ray instruments above the Earth's atmosphere. In the event, although a number of remarkably bright non-solar X-ray sources were discovered from brief sounding rockets flights during the 1960s, convincing evidence for the existence of stellar black holes had to await the launch of the first dedicated satellites, in particular Uhuru and Ariel 5, launched in 1970 and 1974.

Theoretical developments through the 1960s were slowed by the uncertain nature of most cosmic X-ray sources, though the binary star identification of Sco X-1 was a strong stimulus to accretion disc theory (Shakura and Sunyaev 1973). Accretion onto a massive object in the nucleus of an active galaxy (AGN) was considered by Salpeter (1964) and by Zel'dovich and Novikov (1964), and developed with the benefit of more efficient disc accretion by Lynden-Bell (1969). However, it was only after the identification of Cygnus X-1 as a strong black hole candidate that a comparable stellar model was developed by Pringle and Rees (1972) and by Shakura and Sunyaev (1973).

It is hoped that this—necessarily—personal account will provide a useful review of one of the most significant developments in astrophysics during the Space Era.

2 The Origins of X-Ray Astronomy

Prior to the historic discovery (Giacconi et al. 1962) of a remarkably bright X-ray source in the constellation of Scorpius, in June 1962, most astronomers considered that observations in the ultraviolet and gamma ray bands offered the best promise for exploiting the exciting potential of space research. X-ray observations were expected to focus on the study of active stars, with fluxes scaled from that of the solar corona, the only known X-ray source at that time. Predictions ranged up to a thousand times the Sun's X-ray luminosity, but seemed beyond the reach of detection with then-current technology.

In a reflection of the contemporary thinking the recently formed US National Aeronautics and Space Agency (NASA) was planning a series of Orbiting Astronomical Observatories, with the first missions devoted to UV astronomy, although a proposal in 1961 from the UCL and Leicester groups to make simultaneous X-ray observations of the primary UV targets was accepted, and eventually flown on OAO-3 (Copernicus) eleven years later. In the USA, Riccardo Giacconi at American Science and Engineering (ASE) and Bruno Rossi of MIT had, still earlier, published the design of a more ambitious imaging X-ray telescope, with nested mirrors for increased throughput (Giacconi and Rossi 1960), while Rossi made what was to prove a visionary statement in declaring that 'Nature so often leaves the most daring imagination of man far behind'.

The ASE/MIT Aerobee 150 sounding rocket flight from the White Sands Missile Range in June 1962, finding in Sco X-1 a cosmic X-ray source a million time more luminous than the Sun (and brighter than the non-flaring corona at a few keV), began a transformation that laid the foundations for a revolution in High Energy Astrophysics.

Further sounding rocket observations quickly followed, with the US Naval Laboratory group—responsible for still earlier, but unrewarded night-time flights (Friedman 1959)—confirming Sco X-1 and finding a further source in Taurus (Bowyer et al. 1964a). The AS&E group (Gursky et al. 1963), and a team at Lockheed (Fisher et al. 1966) continued with launches from the White Sands missile range, while the British Skylark rocket was used to explore the southern sky from Woomera in South Australia from 1967 (Harries et al. 1967; Cooke et al. 1967), finding several sources in Centaurus and the Galactic centre region, exhibiting both thermal and non-thermal X-ray spectra (Cooke and Pounds 1971). With a hint of what lay ahead, repeated Skylark observations found the X-ray flux from Cen X-3 (first seen by the Lawrence Livermore Group; Chodil et al. 1967) varied by an order of magnitude, while Cen X-2 briefly outshone Sco X-1, before apparently disappearing.

Most sources remained of unknown nature, a notable exception being Tau X-1 which the NRL group had identified with extended X-ray emission from the Crab Nebula supernova remnant in a classic use of the Moon as an occulting disc (Bowyer et al. 1964b). Development of the modulation collimator (Oda et al. 1965), with an important refinement by Gursky, then yielded an arc minute position for Sco X-1 (Gursky et al. 1966), enabling its optical identification with a 13th magnitude blue star (Sandage et al. 1966). By the end of the decade some 20–30 cosmic X-ray sources had been reliably detected, the uncertainty being partly due to many cosmic X-ray sources being highly variable or transient. However, the majority remained unidentified, a major problem being their poorly determined positions on the sky.

The first small orbiting satellites dedicated to observations of cosmic X-ray sources began a transformation which quickly led to X-ray astronomy becoming a major branch of astrophysics. Uhuru led the way in December 1970, being launched into a low equatorial orbit and carrying a large proportional counter array to undertake a deep all-sky survey. Within a few months the extended observations made possible from orbit had shown that many X-ray sources were variable. This led to the important finding that Cen X-3 and Her X-1—and by implication probably many of the most luminous galactic sources—were binary star systems. Moreover, the rapid and periodic X-ray variations of Cen X-3 and Her X-1 showed the X-ray component to be most likely a neutron star.

A second remarkable Uhuru discovery—of extended X-ray emission from galaxy clusters quickly followed—while the number of known X-ray sources increased by an order of magnitude. The 3U catalogue (Giacconi et al. 1974), listing 161 sources, was a key milestone in the development of X-ray astronomy, and the major scientific impact of Uhuru is well recorded in Giacconi and Gursky (1974). The identification of Cygnus X-1 and its recognition as the first strong candidate to contain a black hole is described in more detail in Sect. 3.

Other Uhuru-class satellites followed, with Ariel 5 (UK), SAS-3 (USA) and Hakucho (Japan) dedicated to X-ray observations and OSO-7 (USA) and ANS (Netherlands) being solar and UV astronomy missions carrying secondary X-ray instrumentation. For astronomers in the UK, Ariel 5 brought an ideal opportunity to play a part in the rapid advances taking place. Like Uhuru, Ariel 5 (Fig. 1) was launched on a Scout rocket into a circular near-Earth orbit from a disused oil platform off the coast of Kenya. It carried 6 experiments, the most important in the context of this paper being a Sky Survey Instrument (SSI), similar to that on Uhuru, and an All Sky Monitor (from Goddard Space Fight Center). The Ariel 5 orbit was a good choice, not only in minimising background due to cosmic rays and trapped radiation, but in allowing regular data dumps from the small on-board data recorder. A direct ground and satellite link to the UK provided 6 orbits of 'Quick Look' data from the SSI within an hour of ground station contact. The remaining 'bulk' data were received within 24 hours, an immediacy that contributed substantially to the excitement of the mission operations, while also ensuring a rapid response to new discoveries.

One such discovery was particularly well-timed, with the SSI detecting a previously unseen source in the constellation Monoceros, just 2 days before the start of the first European Astronomy Society meeting, held in Leicester, where new X-ray results from the Ariel 5 and SAS-3 missions dominated the programme. The new X-ray source was to become a further strong black hole candidate, as reported in Sect. 4. In all, some 27 soft X-ray transients were

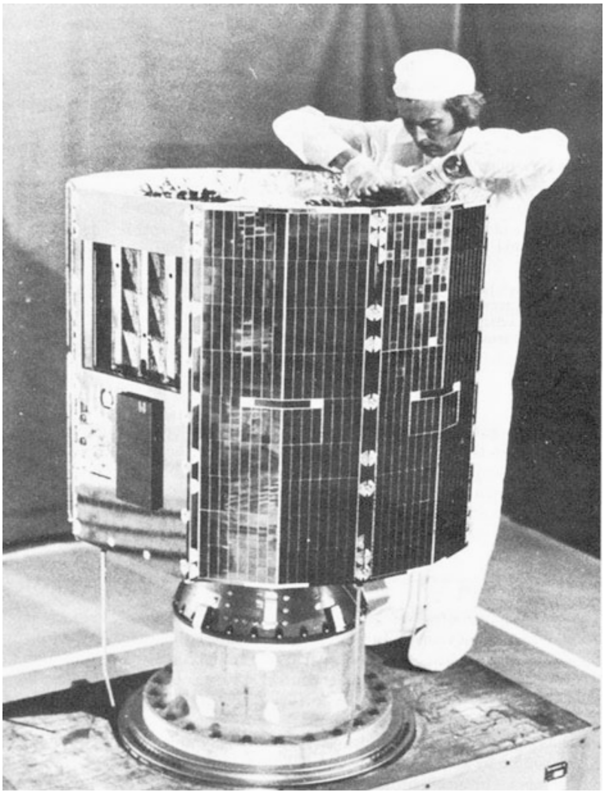


Fig. 1 Ariel 5 spacecraft. The Sky Survey Instrument (SSI) detector array is seen on the *upper left*

discovered as the Ariel 5 mission continued until 1980, though none were as powerful as A0620-00, the majority being neutron star binaries. A second enduring result from the Ariel 5 SSI was in establishing powerful X-ray emission as a characteristic property of Seyfert galaxies. The challenge of correctly identifying many previously unidentified sources, individually located to a few tenths of a sq. deg, was possible only because Seyfert nuclei are also unusually bright in the optical band. While the initial classification was made on a statistical basis, it held up well as new data emerged to establish Seyfert galaxies as a major class of extragalactic X-ray source (Sect. 5).

3 Cygnus X-1

Cygnus X-1 was first detected (Fig. 2) in an NRL Aerobee launch from White Sands in New Mexico in 1964 (Bowyer et al. 1965). Subsequent observations, including a balloon-borne telescope (Overbeck and Tananbaum 1968), showed an unusually hard power law spectrum, not unlike the Crab Nebula, but the lack of an obvious radio or optical counterpart (within the large position uncertainty typical of those early detections) limited detailed investigation.

The unusual nature of Cygnus X-1 became clearer from extended Uhuru observations (Fig. 3) which showed large amplitude fluctuations in the X-ray intensity on timescales down to 100 ms (Schreier et al. 1971), implying a correspondingly small emission region. An improved X-ray source location from Uhuru and an MIT rocket flight (Rappaport et al. 1971) led to the discovery of a weak transient radio source by Braes and Miley (1971) from

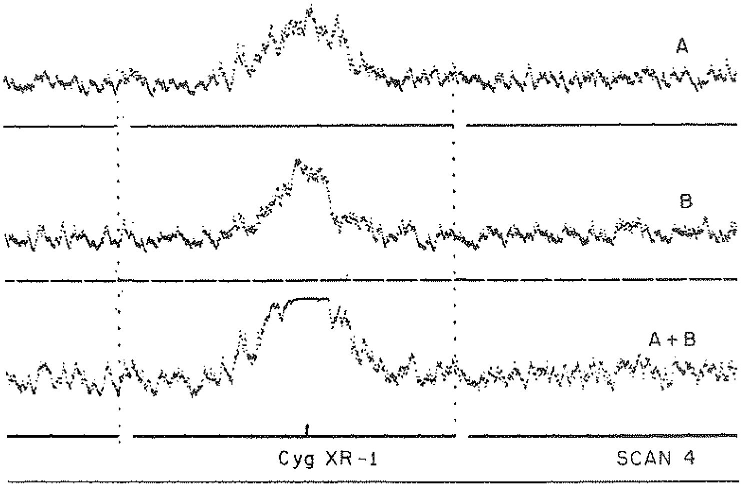


Fig. 2 Telemetry traces from the NRL rocket-borne Geiger counters which first detected Cygnus X-1 in 1964 (Bowyer et al. 1965)

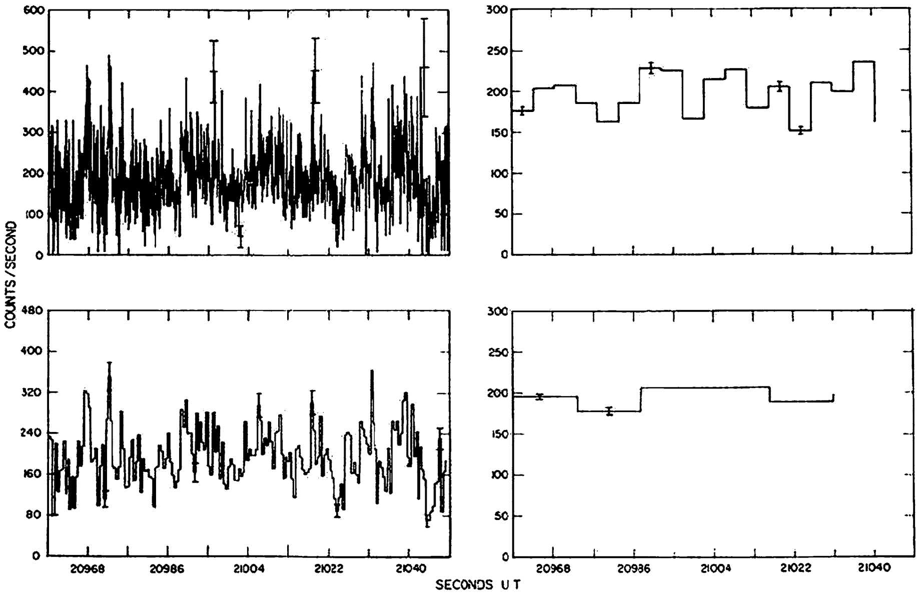


Fig. 3 Uhuru observation of rapid non-periodic variability in Cygnus X-1 binned at 0.096 s, 0.48 s, 4.8 s and 14.4 s. Typical 1σ error bars are shown (Schreier et al. 1971)

Leiden Observatory, and independently by Hjellming and Wade (1971) at the NRAO, which subsequent Uhuru analysis showed to coincide with a change in the X-ray appearance. The greatly improved source position (Fig. 4) finally allowed the optical identification of 'Cyg X-1—a Spectroscopic Binary with a Heavy companion' by Webster and Murdin (1972), at the Royal Greenwich Observatory, and Bolton (1972), at the David Dunlap Observatory in Toronto.

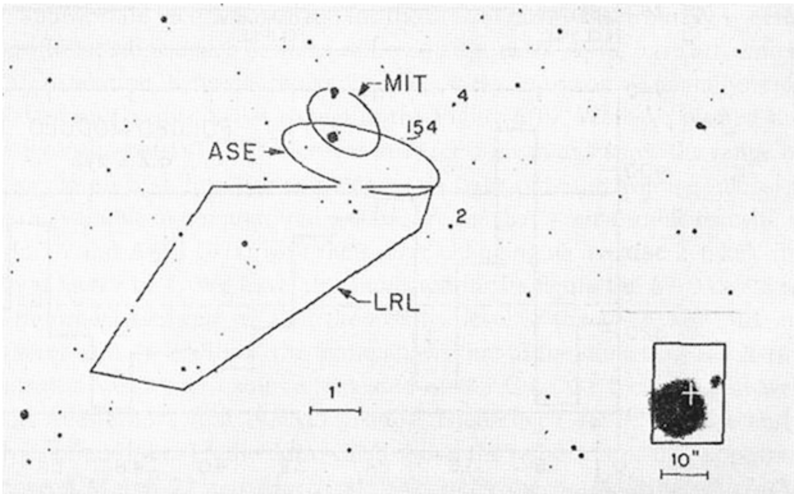


Fig. 4 X-ray observations of Cygnus X-1. HDE 226868 is the bright star in the overlap of the ASE and MIT error boxes. The *insert* shows the more precise coincidence of HDE 226868 with a transient radio source

The 'heavy' companion was HDE 226868, a supergiant star at some 2 kpc distance. Notwithstanding a likely mass of $\sim$30 $M_\odot$, optical spectroscopy showed Doppler shifts of amplitude $\sim$65 $\mathrm{km\,s^{-1}}$ which, together with a binary period of 5.6 days, indicated the unseen (X-ray) companion to have a mass of $\sim$15 $M_\odot$, much larger than the maximum value expected for a neutron star. Cygnus X-1 became widely—though not universally—acclaimed as the first stellar black hole (e.g. Shipman 1975), and understanding the nature of Cygnus X-1 was a primary motivation of theoretical work on accretion discs during that period (see Pringle 1977 for a contemporary review).

VLBA observations in 2009-10 (Reid et al. 2011) finally resolved the long-standing uncertainty in the distance of Cygnus X-1, obtaining a parallax distance of 1.86 ± 0.12 kpc. Re-analysis of extensive X-ray and optical data using the new value has allowed a refinement of the black hole mass of 14.8 ± 1.0 $M_\odot$ (Orosz et al. 2011), and shown that Cygnus X-1 contains a near-extreme Kerr black hole with a spin parameter $a_* > 0.95$, corresponding to a spin rate of $\sim$800 $\mathrm{s^{-1}}$ (Gou et al. 2011).

4 A0620-00

A0620-00 (=V616 Mon) was much the brightest of several X-ray transients discovered by the Ariel 5 satellite during an extended scan of the Galactic plane in autumn 1975. Within 3 days of its first sighting it was brighter than the Crab Nebula, while 2 days later it outshone Scorpius X-1 (Fig. 5), becoming—for a few weeks—the brightest cosmic X-ray source ever seen (Elvis et al. 1975), a record to be held for 30 years. Well before peaking at a flux level $\sim$3 times that of Sco X-1, the new source was being monitored by Ariel 5, SAS-3 and other space- and ground-based telescopes around the world. The X-ray emission then faded over several months, being continually monitored by the Goddard All Sky Monitor on Ariel 5 (Kaluzienski et al. 1975).

Despite being only 30 degrees from the Sun, the optical counterpart of A0620-00, subsequently designated V616 Mon, was rapidly located through its nova-like behaviour (Boley

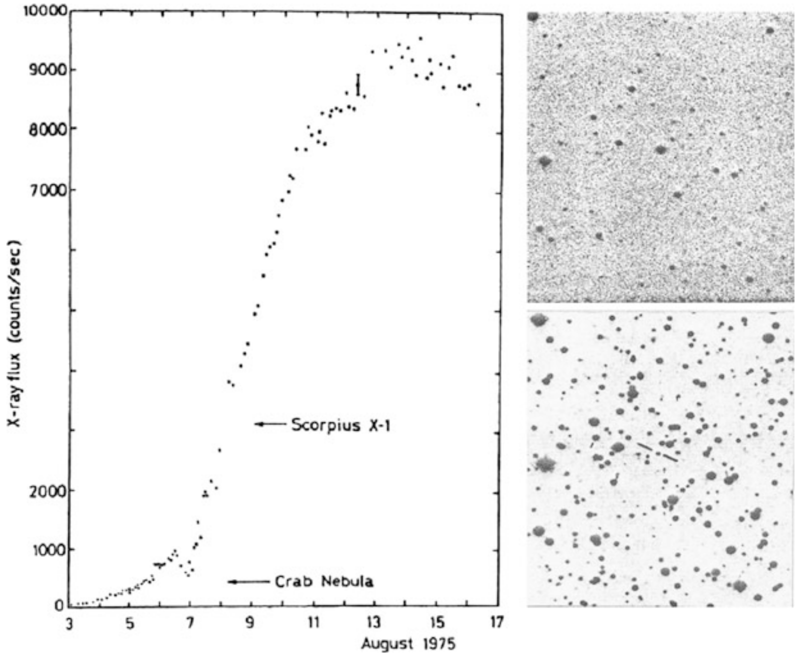


Fig. 5 (*left*) Soft X-ray transient source A0620-00 (Nova Mon) detected in an Ariel 5 Galactic Plane survey. (*right*) Comparison of a short UK Schmidt telescope exposure taken during outburst (*top*) with the corresponding Palomar Sky Survey red plate (*lower*), from which Boley and Wolfson (1975) identified A0620-00 with the K5V star indicated

and Wolfson 1975), the accurate stellar position then allowing identification on the Palomar Observatory Sky Survey charts (Ward et al. 1975) with a $m_B \sim 20$ star (Fig. 5). Ward et al. suggested the faint counterpart was a low mass, solar type star. A radio counterpart was identified with the Mk 2 telescope at Jodrell Bank (Davis et al. 1975), albeit delayed for a week as the telescope was in use by a guest observer.

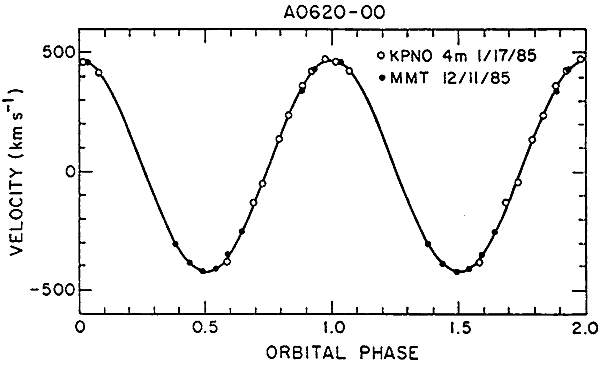
A more detailed optical study, when the nova light had faded, confirmed the companion as a K5V star in a 7.8 hr period binary (McClintock et al. 1983). The small separation of the binary explained why Roche lobe overflow created an accretion disc around the compact companion, with a thermal-viscous disc instability causing the X-ray and optical outburst.

Spectroscopic observation of the binary companion in quiescence revealed the presence of narrow absorption lines, showing an extremely large amplitude radial velocity (Fig. 6) which allowed McClintock and Remillard (1986) to derive a precise value for the binary period, and a Doppler-corrected spectrum of the companion. The outcome was a 3σ lower limit of 3.2 $M_\odot$ for the mass of the compact X-ray source, *independent* of distance and mass of the companion star. With reasonable assumptions regarding the K dwarf star, the lower limit increased to $\sim$7.3 $M_\odot$, well above the maximum mass of a neutron star.

The low mass of the optical counterpart to A0620-00 was critical in enabling the mass of the X-ray star to be determined with greater certainty than for Cygnus X-1, where the large and (at the time) uncertain mass of the companion supergiant led to residual doubts regarding the nature of the X-ray source (e.g. Trimble et al. 1973).

The return of A0620-00 has been forecast for circa 2033, based on the discovery from Harvard plates that V616 Mon previously flared up in 1917, although that return date is

Fig. 6 Radial velocity curve of the companion star to A0620-00. The extreme amplitude and low companion mass provided strong evidence of a black hole (from Charles and Seward 1995)



subject to limitations in modelling the thermal-viscous limit cycle in the accretion disc. Meanwhile, optical studies in quiescence remain of considerable interest, with the detection of rapid optical flaring, with rise times of 30 seconds or less, and a power-density spectrum that may be characteristic of black hole binaries in their low state (Hynes et al. 2003). Hynes et al. concluded that the flares are associated with the accretion flow rather than with an active companion, though it remains unclear whether they originate in the outer disc, or are driven by events in the inner region.

In another important step, using a SAS-3 spectrum taken in 1975 to estimate the radius of the innermost orbit, Gou et al. (2010) have shown the black hole in A0620-00 to be spinning quite slowly, with a spin parameter $a_* = 0.12\pm0.19$, suggesting the radio jet seen in both flaring and quiescent states is probably disc driven.

Finally, a recent determination of the inclination of A0620-00 by Cantrell et al. (2010), has allowed the black hole mass to be further refined to 6.6 ± 0.25 $M_\odot$.

5 Supermassive Black Holes in AGN

A second important contribution from the Ariel 5 Sky Survey to the search for black holes was in establishing powerful X-ray emission as a characteristic property of Seyfert galaxies, alongside the bright optical nucleus and broad permitted lines.

Prior to the launch of Ariel 5 the majority of extragalactic X-ray source identifications were with rich galaxy clusters. Only NGC 4151 and 3C 273 had been identified uniquely with AGN in the 3U catalogue (Kellogg 1974). 60 Uhuru sources at latitude greater than 20 degrees remained unknown and it was suspected that the majority of these unidentified high Galactic latitude sources (UHGLSs) might represent a new form of 'X-ray Galaxy' (Giacconi 1973). The difficulty of identifying many sources at high Galactic latitude, in both Uhuru and Ariel 5 catalogues (Fig. 7), was again due to their positions being known only to a few tenths of a sq. deg.

The Seyfert galaxy NGC3783 was the first new Ariel 5 identification (Cooke et al. 1976), being the brightest object in the 2A1135-373 error box (Fig. 8). Optical spectra obtained with the 3.8m Anglo Australian Telescope (AAT) revealed the presence of [FeX] and other high ionisation lines, further strengthening the X-ray association. Nine further coincidences of bright Seyferts with Ariel 5 sources quickly followed, enabling a report at the 1976 Relativistic Astrophysics meeting in Boston (Pounds 1977) that those 10 Seyfert identifications (Fig. 9), together with 21 new rich galaxy cluster/X-ray identifications, had essentially solved the mystery of the 'UHGLSs'. How a combination of modest gains in source location

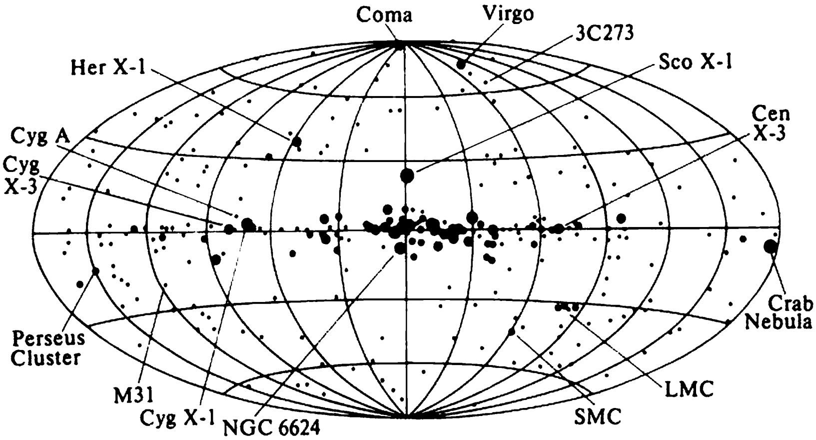


Fig. 7 Map of 297 X-ray sources in the Ariel 5 3A catalogue plotted in Galactic coordinates, with source diameter proportional to the log of the X-ray flux. Many of the faint sources at high Galactic latitude were identified with Seyfert galaxies and galaxy clusters

and in source detection sensitivity allowed the SSI to achieve that breakthrough is recalled by a key participant at the time (Elvis 2012).

A subsequent search of Ariel 5 X-ray error boxes led to the discovery of several previously unknown Seyfert galaxies (Ward et al. 1978), while other Seyfert identifications were found in more precise SAS-3 error boxes (Schnopper et al. 1977, 1978) and from analysis of the final 4U source catalogue (Tananbaum et al. 1978).

Establishing powerful X-ray emission as a characteristic property of Seyfert galaxies was further strengthened when Elvis et al. (1978) showed, for a sample of 15 Seyfert galaxies, that the X-ray luminosity was correlated with the infrared and optical luminosity and with the width of the broad emission lines, but not with the radio flux, strongly suggesting a common origin in the innermost $\leq$0.1 pc.

Although it was by then widely believed that the X-ray emission was produced by accretion onto a supermassive object (see Rees et al. 1981 for a review), confirmation that it was the signature of a supermassive black hole required more information, in particular on the compactness of the emission region. An initial search for tell-tale rapid X-ray variability was disappointing, with a sample of 38 bright AGN observed by HEAO-2 finding no variability on a timescale less than 12 hours (Tennant and Mushotzky 1983).

That crucial next step came from uniquely long uninterrupted observations afforded by the highly eccentric orbit of the ESA satellite EXOSAT (Pallavicini and White 1988). Operational from 1983-86, it was only in the final months when ESA was persuaded to approve observations lasting for a full $\sim$4 day spacecraft orbit. Several bright AGN were accepted as prime targets, since Ariel 5 had found evidence for variability on timescales of days (Marshall et al. 1981). The outcome was remarkable (Fig. 10), finding the X-ray emission from several Seyfert galaxies to vary, with large amplitude (i.e. coherently), on hours or less (Pounds and McHardy 1988). Light travel time arguments showed the X-ray sources to be very compact, with the clear implication that Seyfert X-ray sources were massive analogues of accreting stellar-mass black holes.

Further evidence supporting that conclusion followed with the discovery of 'X-ray reflection' from observations of several Seyfert galaxies with the Japanese GINGA satellite (Pounds et al. 1990; Nandra and Pounds 1994), offering a probe of the optically

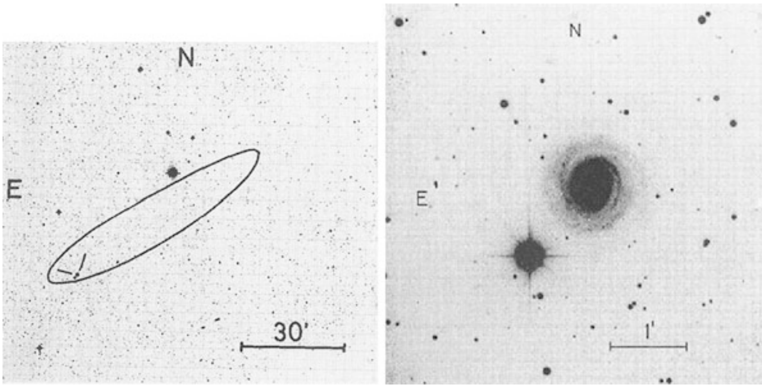
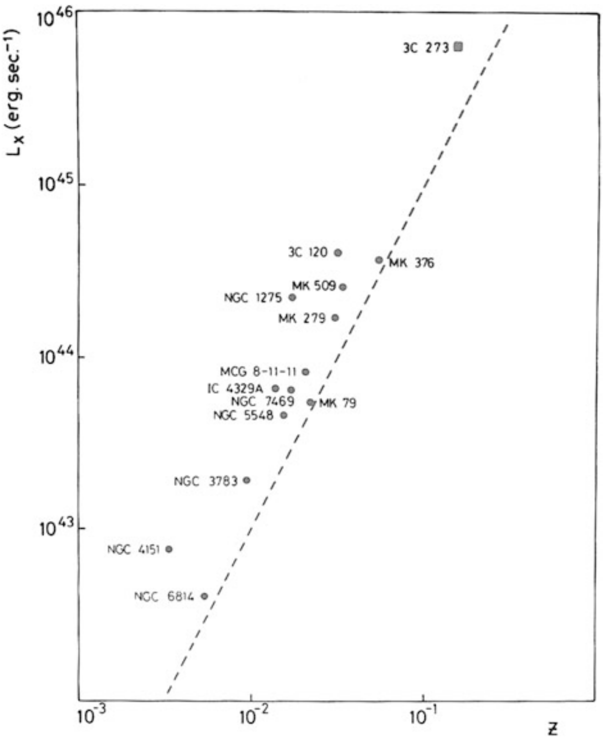


Fig. 8 (*left*) 90 % confidence error box of 2A 1135-373 superimposed on a UK Schmidt Telescope plate. The Seyfert galaxy NGC 3783 is indicated. (*right*) Blue filter 3.8m AAT plate showing the Seyfert galaxy NGC 3783, the first of a new class of X-ray emitters identified with the Ariel 5 SSI

Fig. 9 Luminosity-redshift plot of 13 Seyfert galaxies (10 new) identified in the 2A catalogue, together with the quasar 3C 273



thick matter in the vicinity of the putative black hole. The succeeding Japanese satellite, ASCA, obtained higher resolution spectra which showed the characteristic fluorescent Fe K line associated with reflection to have a broad red wing (Tanaka et al. 1995; Nandra et al. 1997), being widely interpreted as a gravitational redshift, and inspiring a major and continuing research effort to explore the effects of strong gravity in the inner parts of the accretion disc (Fabian et al. 2000).

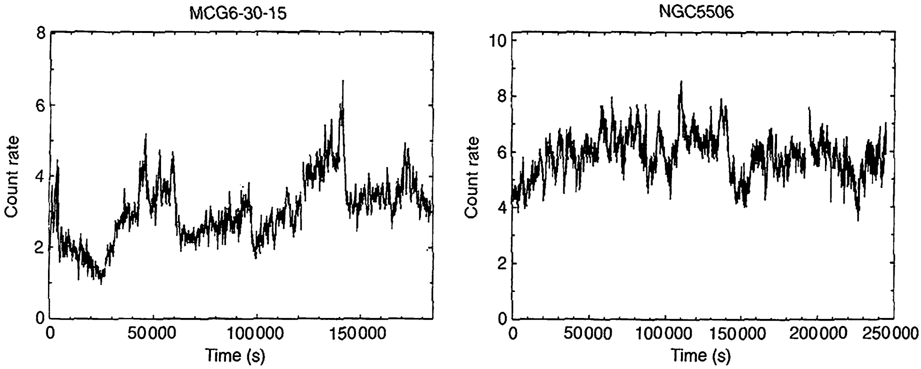


Fig. 10 X-ray light curves of two Seyfert galaxies with rapid, high amplitude variability providing a compelling argument for a supermassive black hole

6 ULXs and Intermediate Mass Black Holes

The discovery of several ultra-luminous X-ray sources (ULX) in nearby galaxies (Fabbiano 1989) has suggested the possible existence of a third class of black hole, with a mass intermediate between the now well-established categories of stellar and supermassive black holes. With X-ray luminosities, assuming isotropic emission, up to $\sim 10^{41}$ erg s^{-1}, the implied black hole mass accreting at the Eddington limit would be $\sim 10^3$ M$_\odot$. The existence of such intermediate mass black holes remains unclear, however, with a strong possibility being that the X-ray flux of a ULX is enhanced by being beamed in our direction (King et al. 2001).

SS433 is an example of a stellar mass black hole with X-ray emission known to be beamed away from the line of sight. In the context of this review it is interesting to note that SS433 remained largely ignored until flagged up by the adjacent Ariel 5 source A1909+04 (Seward et al. 1976). Follow-up observations at the AAT by Clark and Murdin (1978) found a strong emission line spectrum, with several lines they could not identify. Margon et al. (1979) made further observations at the Lick Observatory, finding the unidentified lines to shift in wavelength from night to night. Over the following months it emerged that SS433 is a truly remarkable object, with a pair of jets travelling at relativistic speeds and precessing about a common axis with a 164 day period (Fabian and Rees 1979). While SS433 stands out as an example of extreme super-Eddington accretion in a black hole binary, it can also be seen as a ULX viewed side-on.

7 Summary and Update

Establishing that black holes exist with masses in the range ∼5–15 M$_\odot$ and $\sim 10^6$–10^9 M$_\odot$ has been one of the major scientific returns from space observations. The high luminosity and powerful outflows from black holes, when amply fed, offer exciting prospects for studying the physics of accretion processes that play such a wide role in astronomy, while also exploring matter in regions of strong gravity.

Looking back over 50 years of X-ray astronomy the discovery of A0620-00 still stands out, only the Magnetar SGR 1806 (Palmer et al. 2005) having exceeded its peak X-ray flux. Given the limited sensitivity and infrequent deployment of all-sky X-ray detectors, similar dramatic events may have been missed. The GINGA transient GS2000+25 (Tsunemi et al. 1989) appears to have been similar to A0620-00, but more distant and a factor 6 less bright. Just weeks before this Workshop, on 16 September 2012, the SWIFT GRB monitor triggered on a source in Scorpius which became as bright as the Crab nebula 2 days later, with early indications of being a further 'once in a mission event' (Neil Gehrels in NASA PR). However, the conclusion must be that such events are indeed quite rare.

Ozel et al. (2010) review the mass distribution of stellar-mass black hole candidates, including 23 confirmed black hole binaries. Dynamical data show 17 of those to have low mass optical companions with a narrow distribution of black hole masses, of $7.8 \pm 1.2\ M_\odot$, for the best determined systems. A significant absence of black hole masses between $5M_\odot$ and the neutron star mass limit of $2M_\odot$ was a surprise, which Ozel et al. speculate may be due to a sudden fall in the energy of the supernova explosion with increasing progenitor mass.

Binary periods for the low mass transient systems range from $\sim$4 hr to $\sim$6 d (an exception being GRS 1915+105), and $\sim$32 hr to $\sim$5.6 d for the persistent high mass sources, comfortably meeting the requirement anticipated in the Introduction for copius mass transfer by Roche lobe overflow. Such powerful X-ray sources will be the exception, of course, with the vast majority of Galactic black holes being limited to inefficient Bondi (radial) accretion from the local ISM, and much too faint to be detected.

Since launch in 2004 the NASA Swift satellite has been detecting $\sim$100 Gamma Ray Bursts (GRB) each year (Gehrels and Meszaros 2012), with the few-arc-sec positions obtained by rapidly detecting the X-ray afterglow allowing many bursts to be optically identified. Many GRB are found to be associated with supernovae in galaxies at high redshift. With a likely origin in the collapse of a massive star (MacFadyen and Woosley 1999), the remarkable inference is that Swift is observing the birth of stellar mass black holes from across the Universe, at a rate—allowing for beaming and other factors—of $\sim 10^5$ a year.

One unusually long event observed by Swift in March 2011 has been interpreted as the capture of a star by a SMBH (Burrows et al. 2011; Levan et al. 2011), prefacing an important new way of studying timescales in the accretion disc of an AGN. Follow-up X-ray observations with Suzaku and XMM-Newton detected Quasi Period Oscillations (QPO), with a transient periodicity at 3.5 minutes, evidently relating to processes very close to the innermost stable circular orbit (Reis et al. 2012). That transient event adds to the first reliable QPO detection in an AGN (Gierlinski et al. 1998), providing a further example of the similarities in disc physics shared by accreting black holes in X-ray binaries and AGN.

The interpretation of flickering in the emission from Sgr A as the disruption of passing asteroids (Zubovas et al. 2012) provides a further indication that the feeding of SMBH will range from short sub-Eddington events to less frequent minor and major mergers. However, mergers seem more likely to have led to the heavily dust-obscured galaxies (DOGS) found in the WISE sky survey (NASA PR 29/8/12); NuStar observations should confirm whether these are super-Eddington AGN.

The study of supermassive black holes has been a major beneficiary of three powerful X-ray observatories, Chandra, XMM-Newton and Suzaku, launched since 1999. Long exposures on HST deep fields have shown, via coincident X-ray emission, that powerful X-ray emission—and implicitly the presence of supermassive black holes—extends to AGN at high redshift. The high angular resolution of Chandra resolved two point-like X-ray sources near the centre of NGC 6420 (Fig. 11), believed to be a pair of merging galaxies (Komossa et al. 2003). The eventual merger of the SMBHs will be a spectactular event, with a substantial fraction of the combined rest mass released over a few hours, mainly as a QPO gravity wave outburst.

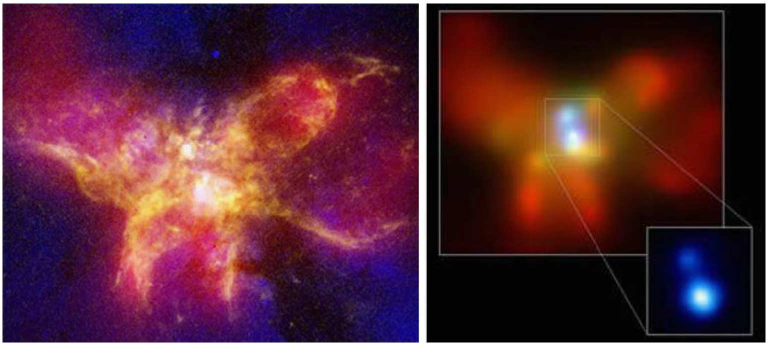


Fig. 11 Optical and Chandra images of NGC 6420, believed to be a pair of merging galaxies. The two bright point-like X-ray sources in the *right hand panel* are probably SMBH at the respective nuclei

Finally, as discussed elsewhere at this Workshop, highly ionised outflows with velocities ∼0.1–0.2c were first detected in X-ray spectra of non-BAL AGN a decade ago (Pounds et al. 2003; Reeves et al. 2003). Subsequent observations (Cappi 2006) and searches of the XMM-Newton (Tombesi et al. 2010, 2011) and Suzaku (Gofford et al. 2013) data archives have shown such ultra-fast outflows to be a common feature of luminous AGN, indicating that powerful black hole winds are likely to have a wider importance in galaxy feedback models.

Acknowledgements The outstanding efforts of many colleagues and former students enabled the X-ray Astronomy Group at Leicester to play a key role in establishing the existence of black holes in both stellar systems and in the nuclei of Active Galaxies. That opportunity was, of course, only possible by building on the pioneering achievements of other scientists and engineers who have established X-ray astronomy as a vibrant discipline in Space Science. Grateful thanks are also due to Jeff McClintock, Paul Gorenstein and Martin Ward who provided valuable comments on the draft manuscript.

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General Overview of Black Hole Accretion Theory

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Abstract I provide a broad overview of the basic theoretical paradigms of black hole accretion flows. Models that make contact with observations continue to be mostly based on the four decade old alpha stress prescription of Shakura and Sunyaev (1973), and I discuss the properties of both radiatively efficient and inefficient models, including their local properties, their expected stability to secular perturbations, and how they might be tied together in global flow geometries. The alpha stress is a prescription for turbulence, for which the only existing plausible candidate is that which develops from the magnetorotational instability (MRI). I therefore also review what is currently known about the local properties of such turbulence, and the physical issues that have been elucidated and that remain uncertain that are relevant for the various alpha-based black hole accretion flow models.

Keywords Accretion · Accretion disks · Black hole physics · Instabilities · MHD

1 Introduction

Accretion is the very process that allows black hole sources to emit electromagnetic radiation and other forms of energy. Because black holes are so small in size compared to the spatial scale of their sources of fueling, and because centrifugal forces on matter of given angular momentum increase more rapidly ($\propto R^{-3}$) than gravity ($\propto R^{-2}$) as one moves inward in radius R, accretion is generally believed to be a process involving rotationally supported flows. Matter in such a flow must lose angular momentum in order to move inward and release gravitational binding energy. It is the nature of the angular momentum loss mechanism, and the process whereby gravitational binding energy is converted into observable forms of energy, that are the two central questions of black hole accretion theory. At least three mechanisms have been proposed for angular momentum extraction:

(1) *External stresses associated with large scale magnetic fields in a magnetohydrodynamic (MHD) outflow*. This mechanism (Blandford and Payne 1982) may be relevant in low

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luminosity sources where accretion power may be largely converted into mechanical power in outflows. It may also be relevant in resolving the fueling and self-gravity problems in the outer accretion flows in active galactic nuclei (Goodman 2003). Whether and how large scale magnetic fields can be created remains an open question, however.

(2) *Magnetorotational (MRI) turbulence*. Such turbulence is generic for plasmas that are sufficiently electrically conducting and not too strongly magnetized (Balbus and Hawley 1991, 1992, 1998; Hawley and Balbus 1991). Because turbulence is inherently dissipative, this process is almost certainly relevant for sources whose power output is dominated by thermal radiative emission mechanisms.

(3) *Nonaxisymmetric waves and shocks*. Nonaxisymmetric (e.g. spiral) waves can transport angular momentum outward through the flow. Such waves can also transport energy away from the region where gravitational binding energy is released, depositing it elsewhere. Waves are almost certainly relevant in disks around supermassive black hole binaries, and also in the outer, self-gravitating parts of disks in active galactic nuclei. They probably also play a role in the outer parts of black hole X-ray binary disks due to tidal excitation by the companion star. Nonaxisymmetric shocks can also play an important role in the inner regions of accretion flows whose angular momenta are misaligned with the black hole spin axis (Fragile and Blaes 2008).

Among these options, only the second—MRI turbulence—is a mechanism that *might* be describable by the classical alpha prescription of Shakura and Sunyaev (1973), at least in some aspects (Balbus and Papaloizou 1999). The angular momentum transporting stress $w_{R\phi}$ in the turbulence is given by local space and time averages of correlated fluctuations in radial (R) and azimuthal (ϕ) fluctuations of velocity $\mathbf{v}$ (the Reynolds stress) and magnetic field $\mathbf{B}$ (the Maxwell stress),

$$w_{R\phi} = \left\langle \rho v_R \delta v_\phi - \frac{B_R B_\phi}{4\pi} \right\rangle, \tag{1}$$

where ρ here is the mass density and δv_ϕ is the local deviation of the azimuthal velocity component from the mean background shear flow. Maxwell stresses are generally larger in magnitude than the Reynolds stresses by factors of at least several. I say that the total stress *might* be describable by the classical alpha prescription because these stresses appear to be mostly local in the sense that simulations show that radial correlations in stress drop rapidly on scales larger than the local disk scale height. However, as I discuss in Sect. 3.1 below, there remain correlations on larger radial scales.

This article provides a broad overview of alpha-based models of black hole accretion flows, focusing on structure, dynamics, and thermodynamics. These models continue to dominate theoretical efforts to explain observations, but a slow revolution is occurring as simulations of MRI turbulence, both local and global, continue to become more powerful and to incorporate more and more of the relevant physics. This article will also discuss what has been learned recently from local, shearing box simulations of MRI turbulence as this pertains directly to some of the alpha-based modeling. A review of global simulations can be found in Chap. 2.4. Spectral modeling of accretion flows is discussed in Chap. 2.3. I will also mainly focus on *accretion* rather than the formation of jets and outflows here, though jets and outflows are clearly important (both observationally and theoretically, in certain flow states). See Chap. 5.3 on jet launching mechanisms.

2 Hydrodynamic Disk Models with the Alpha Prescription

Decades of theory and models of black hole accretion flows have critically relied on the alpha prescription for a local stress introduced by Shakura and Sunyaev (1973). There are

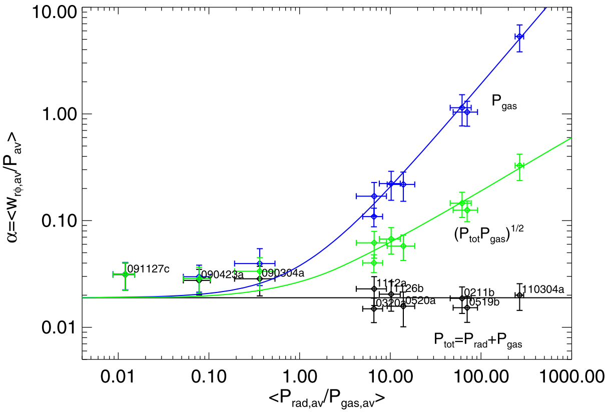

Fig. 1 Time-averaged values of the ratio of spatially averaged stress to various measures of spatially averaged thermal pressure, i.e. the Shakura and Sunyaev (1973) parameter alpha, as a function of the time-averaged ratio of spatially averaged radiation pressure to spatially averaged gas pressure, for a number of radiation MHD, vertically stratified, shearing box simulations of MRI turbulence. *Black*, *green* and *blue points* are the results for thermal pressures defined to be the total (radiation plus gas) pressure, the geometric mean of the total and gas pressures, and the gas pressure alone, respectively. *Horizontal* and *vertical error bars* on all points indicate one standard deviation in the respective time-averages. The *horizontal black line* is the average alpha value of the total pressure prescription (black) points, while the *green* and *blue curves* are what would result if the total pressure prescription were correct, but one nevertheless insisted on defining alpha in terms of the other thermal pressure definitions used in the green and blue points, respectively. The stress prescription that is most consistent with the simulation data is one in which the total thermal pressure is used, though it is perhaps noteworthy that the alpha values in the gas pressure dominated simulations are consistently higher than the alpha values in the radiation pressure dominated simulations (Updated from Hirose et al. 2009)

numerous variants of this prescription which produce order unity changes in the definition of α, and one of the most common is

$$w_{R\phi} = \alpha P, \tag{2}$$

where P is the thermal pressure. Most models have assumed that this is the *total* thermal pressure (gas plus radiation), but prescriptions in which the stress is taken to be proportional to just the gas pressure alone (e.g. Sakimoto and Coroniti 1981) or the geometric mean of the gas and total thermal pressures (e.g. Taam and Lin 1984) have also been suggested. However, as illustrated in Fig. 1, recent radiation MHD simulations of MRI turbulence find that the stress scales best with total thermal pressure, at least on long time scales (Ohsuga et al. 2009; Hirose et al. 2009).

The alpha prescription (2) is usually used to solve for the radial structure of vertically-integrated geometrically thin or slim accretion disks, in which case it enters the equations through the vertically-integrated stress:

$$W_{R\phi} = \int_{-\infty}^{\infty} w_{R\phi} dz \sim 2H\alpha P, \tag{3}$$

where P is now some vertically averaged thermal pressure, of order the midplane pressure, and H is the vertical half-thickness of the disk. This is consistent with MRI simulations, but the prescription is also occasionally used even more locally by assuming that the vertical profiles of stress and dissipation at a given radius are proportional to the local vertical profile of thermal pressure. As we discuss below in Sect. 3.2, this is not consistent with vertically stratified simulations of MRI turbulence, which generally have vertical profiles of stress that are broader than the thermal pressure profile. Alpha defined locally would therefore increase rapidly outward from the disk midplane.

2.1 Local Thermal Equilibria and Secular Instabilities

Virtually all (non-simulation-based) models of black hole accretion flows are based on vertically integrated hydrodynamic equations. These models often neglect the possibility of significant losses of mass, angular momentum, and energy in outflows and jets, though some models do attempt to include them with various prescriptions, particularly in advection-dominated flows which we will come to shortly. As discussed in Chap. 5.1, neglect of outflows is likely to be a bad approximation in some sources and accretion states. Nevertheless, if we adopt this assumption for simplicity, then for stationary flows, the conservation laws of mass, radial momentum, angular momentum, and internal energy can be written as

$$\dot{M} = 2\pi R \Sigma v, \tag{4}$$

$$\rho v \frac{dv}{dR} = \rho\left(\Omega^2 - \Omega_{\rm K}^2\right)R - \frac{dP}{dR}, \tag{5}$$

$$\dot{M} \frac{d\ell}{dR} = \frac{d}{dR}\left(2\pi R^2 W_{R\phi}\right), \tag{6}$$

and

$$Q_{\rm adv} \equiv \frac{-\dot{M}}{4\pi R}\left[\frac{dU}{dR} + P\frac{d}{dR}\left(\frac{1}{\rho}\right)\right] = Q^+ - Q^-, \tag{7}$$

where we have neglected general relativity for the purposes of physical transparency. Here $\rho \sim \Sigma/(2H)$ is a vertically-averaged density, Σ is the surface mass density, Ω is the fluid angular velocity which may differ from the test particle (Kepler) angular velocity $\Omega_{\rm K}$, $\ell = \Omega R^2$ is the fluid specific angular momentum, v is the inward radial drift speed, U is a vertical average of the internal energy per unit mass, Q^- is the radiative cooling rate per unit surface area on each face of the disk, $Q^+ = -(1/2)W_{R\phi}Rd\Omega/dR$ is half the turbulent dissipation rate per unit surface area, and $Q_{\rm adv}$ is half the inward radial advection of heat per unit surface area. Vertical hydrostatic equilibrium implies that the vertical half-thickness of the disk is $H \sim (P/\rho)^{1/2}/\Omega_{\rm K}$.

Once one adopts the alpha prescription (2), together with an equation of state and opacities and/or optically thin cooling functions, it is possible to solve these equations with assumed boundary conditions to derive the radial profiles of vertically-averaged fluid variables in the flow. Such models generally invoke a regularity condition at an inner sonic point and/or a no-torque inner boundary condition at, for example, the innermost stable circular orbit, although magnetohydrodynamic stresses can be important once one enters the plunging region near the black hole (Gammie 1999; Krolik 1999). (See Chap. 2.4 and, e.g., Penna et al. 2010 and Noble et al. 2010 for recent simulation work on this issue for geometrically thin disks.) Another approach is to consider radii much larger than the gravitational radius $R_{\rm g} \equiv GM/c^2$ and invoke self-similarity by assuming a constant ratio of advective cooling over turbulent dissipation $Q_{\rm adv}/Q^+$ (Narayan and Yi 1994).

For a fixed black hole mass, models that are stationary generally depend on a number of chosen parameters, the most important being the accretion rate $\dot{M}$ which is everywhere constant through the flow (remember, we are neglecting outflows here). A number of possible equilibria have been discovered in this way, and the primary method of choosing which