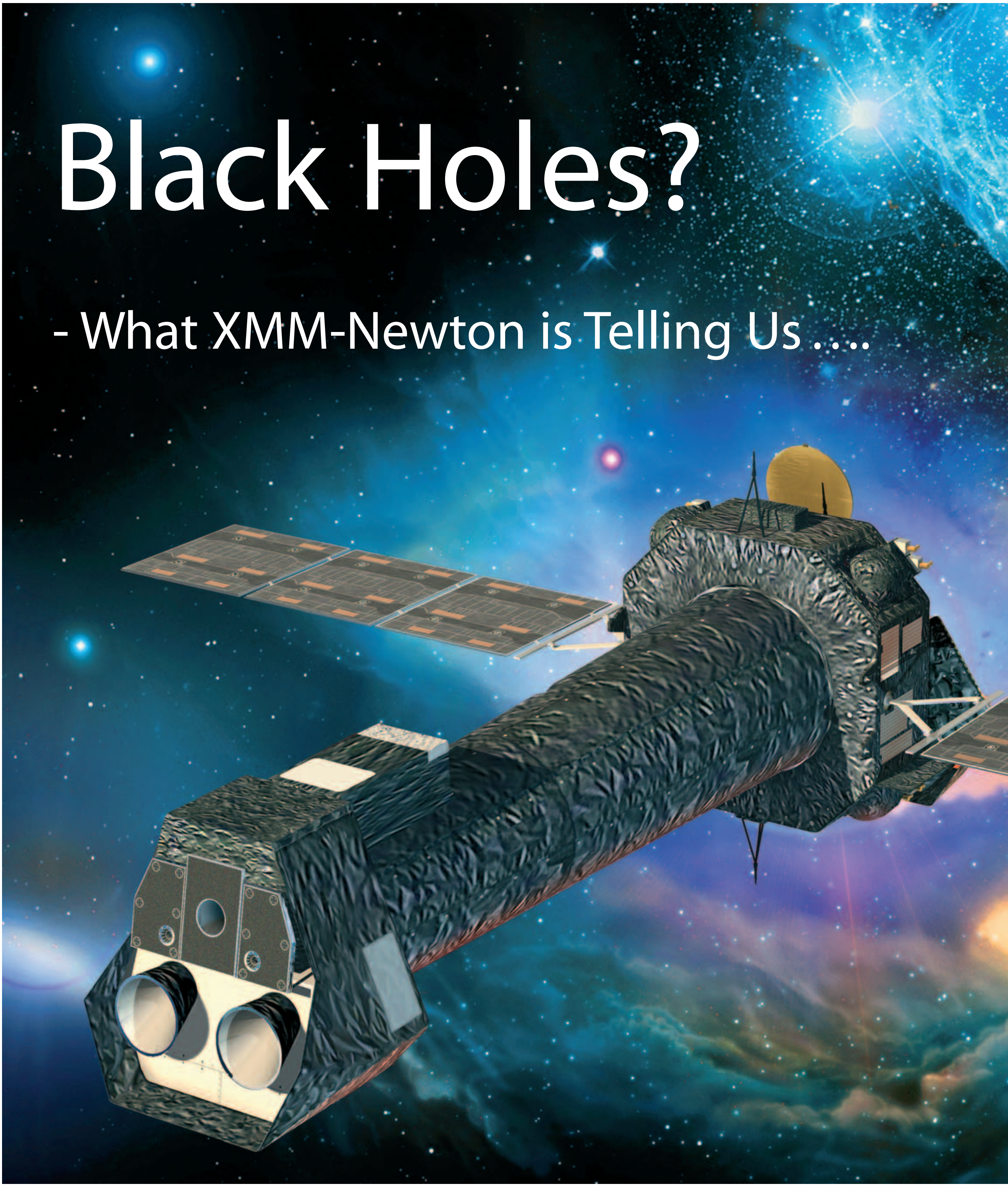
Black Holes?

- What XMM-Newton is Telling Us ....



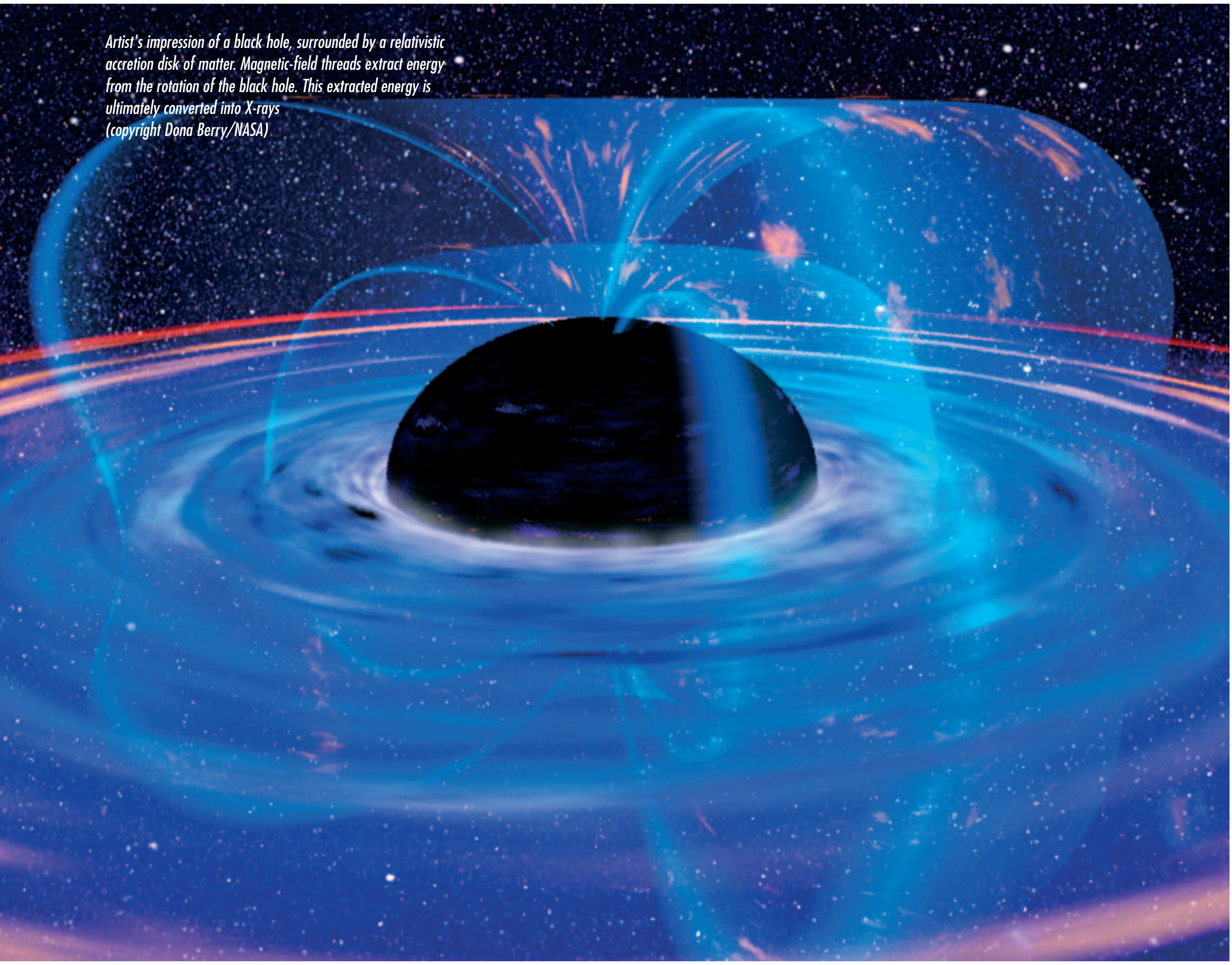
The incredibly powerful 'X-ray eyes' of ESA's XMM-Newton scientific satellite, launched in December 1999, are shedding new light on one of the most obscure mysteries in our Universe, namely the physical nature of black holes and the cosmic gas and dust that surrounds them.

Matteo Guainazzi
XMM-Newton Science Operations Centre,
ESA Directorate of Scientific Programmes,
Villafranca, Madrid, Spain

Black Holes: The Myth of Elusiveness

Most of the debate about the existence of black holes that took place during the 20th century was centred around the final states of massive stars. There are good reasons to believe that stars larger than four solar masses cannot avoid complete gravitational collapse. Under these conditions, the ultimate fate of stellar evolution is a 'space-time singularity' with infinite density. Nothing trapped within a black hole can escape the formidable pull of gravitation, so if black holes exist how could we observe them? By their very definition, black holes are invisible. How then can we hope to detect a celestial object that cannot communicate with us on any wavelength?

Indeed, isolated black holes are very hard to detect. Although one can speculate that some micro-lensing events might be associated with black holes in our Galaxy, the most efficient – and probably currently the only – scenario that allows their detection is through matter which is pulled in towards and eventually swallowed by them. Before encountering its ultimate fate beyond the 'horizon' of the black hole, the infalling matter is heated to temperatures of the order of 1 to 10 million degrees. The peak in the radiation emitted as a result of that


Artist's impression of a black hole, surrounded by a relativistic accretion disk of matter. Magnetic-field threads extract energy from the rotation of the black hole. This extracted energy is ultimately converted into X-rays (copyright Dona Berry/NASA)

cataclysmic heating lies in the X-ray band. X-rays are therefore the best available 'probe' with which to study the properties of cosmic black holes and their environment.

A black hole is a very simple object in mathematical terms in that it can be fully described by knowing just three parameters: its mass, its charge, and its angular momentum. We still have no experimental way to directly measure their charge, but X-ray measurements can tell us quite a lot about a black hole's angular momentum. Likewise, we know surprisingly little about the properties of the environment surrounding cosmic black holes, which are crucially shaped by the gravitational forces that are at work (the so-called 'gravitational well'). ESA's XMM-Newton mission is allowing us to make great strides in this respect.

Black Holes in Our Own Galaxy

The first experimental proof for the existence of black holes in our own 'neighbourhood' was obtained from the X-ray-emitting binary star system Cyg X-1, in which a 'normal star' orbits around an 'invisible object'. If the stellar mass, the orbital period, and the amplitude of the velocity curve are known, the mass of the invisible object can be estimated. This method yields values of between 7 and 17 times the mass of the Sun for Cyg X-1.

Today, a total of 18 black-hole binary systems are known, which represent only a very tiny fraction of the some 300 million black-hole systems that are believed to exist in our own Galaxy. The major contributions of XMM-Newton to our knowledge about such galactic black holes include the discovery of relativistically distorted emission-line profiles, and the study of large X-ray flares from the source Sgr A*, close to the Galactic Centre.

Key Concepts in Deciphering the XMM-Newton Data

Micro-lensing: According to the general theory of relativity, photons feel the pull of gravity like ordinary matter does. A light wave traveling close to a large mass concentration - such as a galaxy or a black hole - will be bent. This may produce multiple identical images of a background object or, in the extreme case of perfect alignment, a 'ring of light' around the foreground object.

Angular momentum: In classical mechanics, this is the product of the mass times the rotational speed.

Fluorescence: The physical process whereby absorption of a photon by the inner electron shells of an atom (photo-absorption) is followed by (mostly) line emission, produced by the cascade of higher level electrons onto the emptied level. 'K-fluorescence' refers to the fluorescence process involving the K atomic shell.

Doppler shift: If a source of light is moving towards us, the energy of the photons that we detect is higher than originally emitted by the source. This phenomenon is called 'Doppler blueshift'. The reverse, Doppler redshift, is observed in galaxies due to the expansion of the Universe. Matter distributed in spiraling disks may exhibit both blue- and redshift, as part of the disk approaches us and part recedes from us.

Gravitational redshift: Photons subject to a gravitational force lose energy, i.e. they become 'redder'. This effect is not negligible only when the pull of gravity is extremely strong, such as close to a black hole.

Resolution: This concept relates to an instrument's ability to discriminate between two events occurring very close together in an observational parameter space. Spatial resolution means being capable of distinguishing two celestial sources that are physically very close together in the sky. Energy resolution means distinguishing two absorption or emission lines that are very close in energy, while temporal resolution means distinguishing two events that happen very close together in time.

The Scientific Instruments aboard XMM-Newton

XMM-Newton carries two different classes of X-ray instrument. The three European Photon Imaging Cameras (EPICs) – two based on PN-CCD technology and one based on MOS-CCD technology – provide images of the X-ray sky, as well as spectra with moderate resolution and flux time series. Three Reflection Grating Spectrometers (RGSs) produce spectra with very high energy resolution. An Optical Monitor complements the X-ray instrumentation. The main scientific characteristics of the X-ray instruments are as follows:

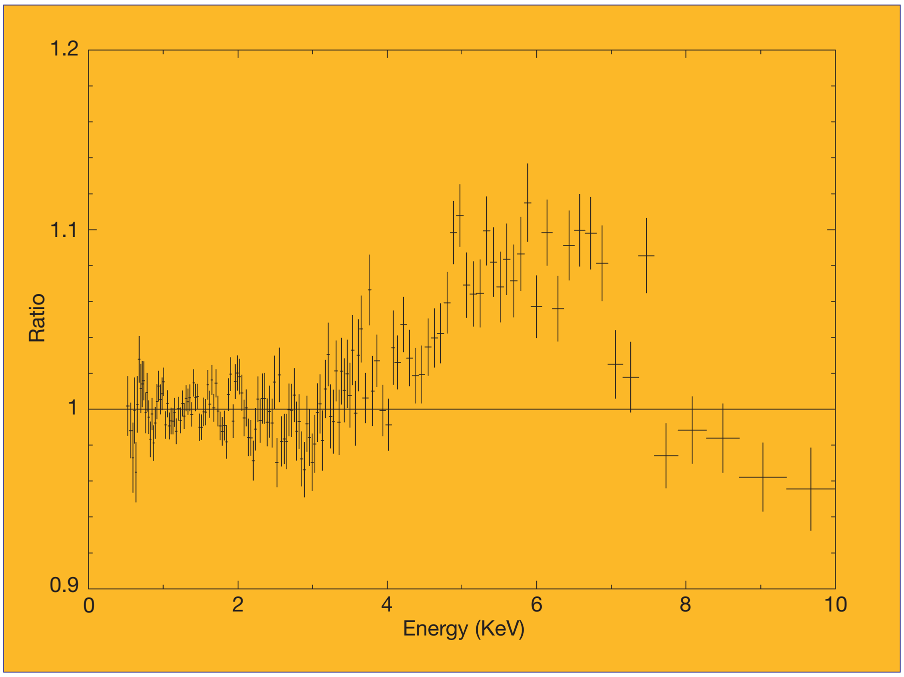
	PN-based EPIC	MOS-based EPIC	RGS
Energy Bandpass (keV)	0.15-15	0.15-12	0.35-2.5
Field-of-View (arcmin)	30	30	5
Spatial Resolution (arcsec)	6	5	N/A
Temporal Resolution (ms)	1.5	.03	16
Energy Resolution at 1 keV (eV)	80	70	3.2

Relativistic Effects in Galactic Black-Hole Systems

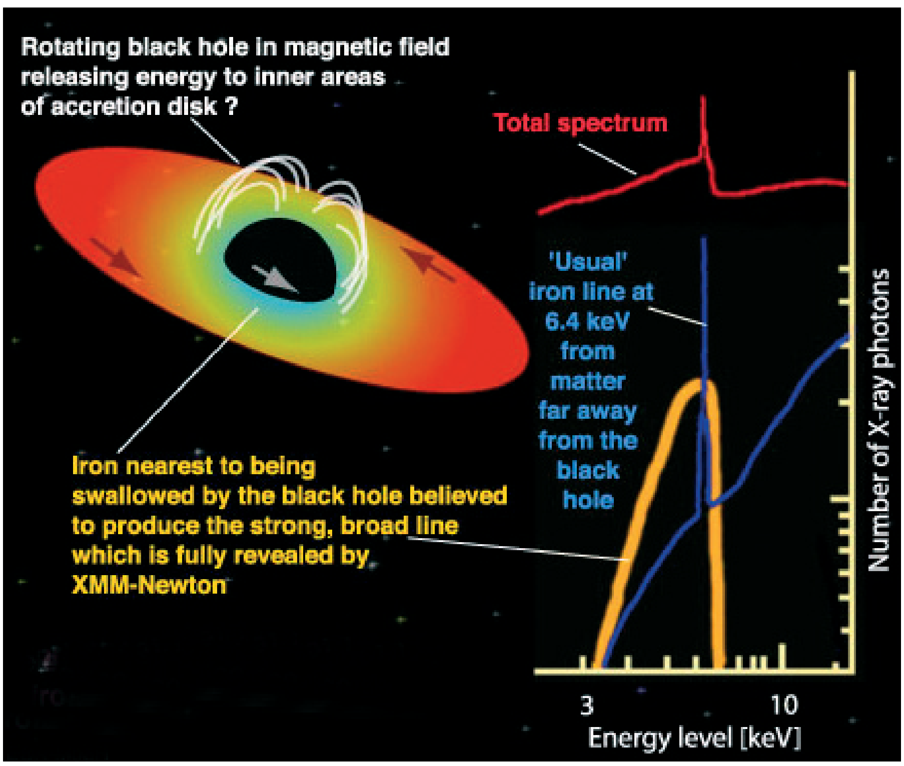
The accompanying illustration shows the energy spectrum of the black-hole candidate XTE J1650-500 as measured by XMM-Newton. The broad excess feature is interpreted as an iron K_{α} fluorescent emission line. The presence of this iron line is in itself neither news nor a surprise. Matter in the vicinity of super-massive black holes will most likely be illuminated by a large flow of X-rays, and produce fluorescent lines in the energy range of 6.40 to 6.96 keV, depending on the dominant iron ionisation stage. However, in XTE J1650-500 the excess feature extends to energies as low as 4 keV. How is this possible?

A scheme for the process responsible for the broadening of emission lines emitted close to black holes is shown in the illustration below. The combination of Doppler and gravitational-redshift effects in a disc of matter spiraling around the black hole could significantly distort the profile of an originally mono-energetic emission line. The line profile depends partly on the black hole's angular momentum: the larger the angular momentum, the closer the accreting matter can approach the event horizon. The iron-line profile observed in XTE J1650-500 is consistent with a black hole rotating at its maximum possible speed, according to the general theory of relativity. This result represents the first observational evidence that black holes in our Galaxy rotate, and it allows us to determine one of the three basic parameters that characterise their physical nature.

Another interesting conclusion could be drawn from the XMM-Newton measurements made by J. Miller et al. in 2002. The more photons (in relative terms) that are produced close to the black hole, the stronger is the relativistic distortion of the iron-line profile. The profile observed by XMM-Newton also requires an extreme concentration of photon-emitting matter close to the black hole, to be consistent with standard accretion-disk models. This

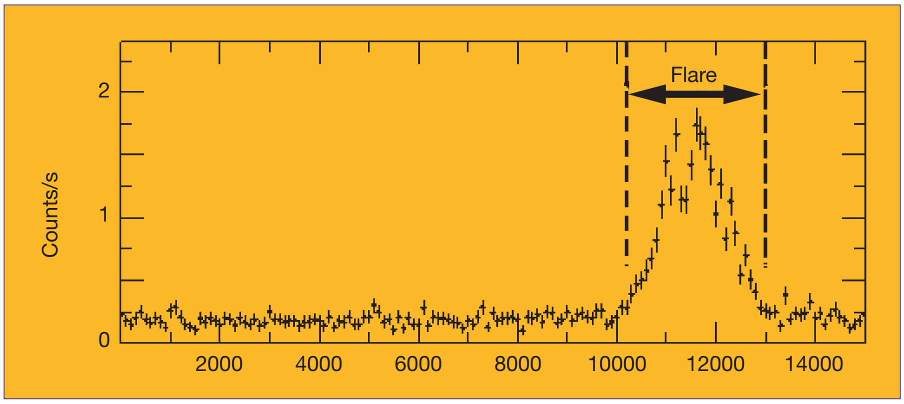


The XMM-Newton energy spectrum of the black-hole candidate XTE J1650-500
(from J. Miller et al., Astrophysical Journal, 2002)



This scheme shows how emission lines could be broadened, when emitted by matter orbiting in an accretion disk around a black hole (top left). Photons, originally emitted at a given energy (blue profile in the spectrum on the right) are shifted towards lower and higher energy by the Doppler effect, and towards lower energies by gravitational redshift (orange profile). The final line profile (red) looks very different from the original one. This particular figure refers to the active galaxy MCG-6-30-15, but the same phenomenon also occurs in galactic black holes like XTE J1650-500
(copyright ESA)

is interpreted as evidence for energy being extracted from the rotating black hole, a fundamental general relativistic prediction, foreseen by R.D. Blandford and R.L. Znajek more than 25 years ago but never verified experimentally before. Once again, XMM-Newton’s unique and powerful X-ray eyes have provided a glimpse of the basic properties of black-hole physics, which had previously only existed in the imaginative minds of the theoreticians.

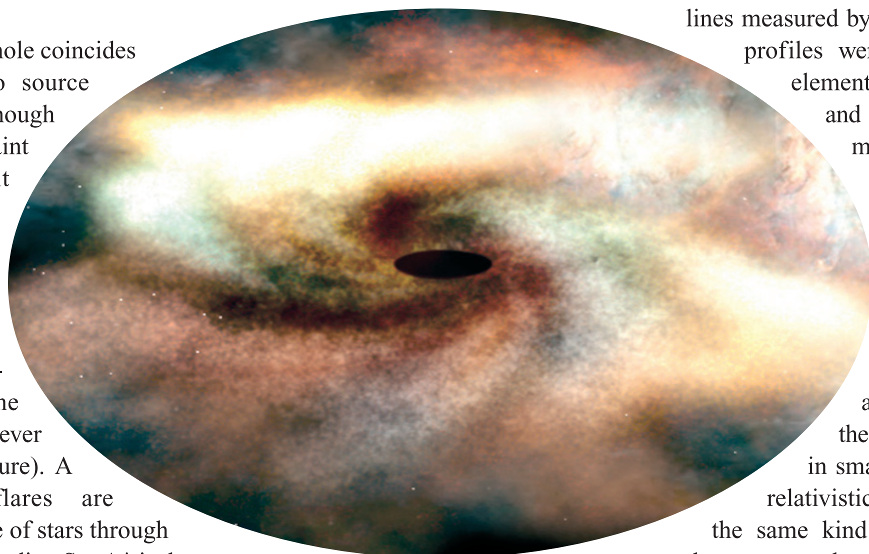


The Sgr A X-ray flare event in October 2002 as observed with XMM-Newton’s EPIC instrument in the 2 to 10 keV energy band (from D. Porquet et al., Astronomy & Astrophysics, 2003)*

The Star-swallowing Monster at the Centre of Our Galaxy

The most massive black hole in our own Galaxy is probably located close to its centre. High-resolution infrared observations have shown that stars in the most central region of the Milky Way are orbiting around a ‘dark mass’ about 1 million times greater than that of the Sun, and concentrated within a region of space about $5x10^8$ times smaller than our own Galaxy’s diameter. A black hole is the only viable explanation.

The suspected black hole coincides with a compact radio source known as Sgr A*. Although Sgr A* is remarkably faint in optical terms, it undergoes extraordinary X-ray flaring events. After their discovery by the American X-ray satellite Chandra in October 2000, XMM-Newton detected the brightest Sgr A* flare ever (see accompanying figure). A scenario whereby flares are triggered by the passage of stars through an accretion disk surrounding Sgr A* is the most likely explanation for the massive event that XMM-Newton observed.



Black Holes at the Centre of Other Galaxies?

Around 10% of known galaxies are ‘active’ in that their luminosity is dominated by a very compact core close to their centre. The energy emitted from these so-called ‘Active Galactic Nuclei’ (AGNs) can be 10 000 times as great as the total stellar light from our Galaxy. Already in the late 1960s, the hypothesis was put forward that this enormous power must ultimately be produced by the accretion of matter onto a ‘super-massive’ black hole – where ‘super-massive’ means between 100 000 and 1 billion times the mass of the Sun.

Are Super-massive Black Holes Shy?

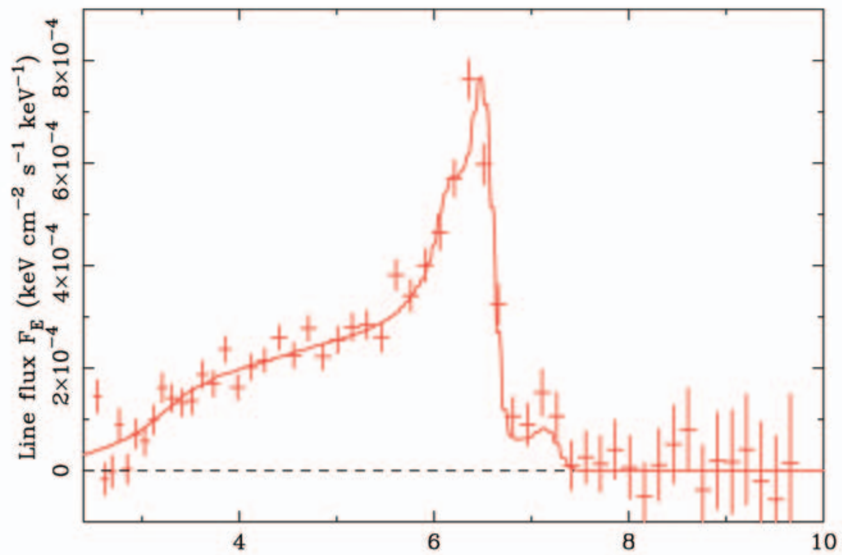
Although originally developed to explain the X-ray spectrum of Cyg X-1, the relativistic-line-profile distortion scenario has mostly been applied to nearby AGNs. The earliest results obtained by the Japanese Advanced Satellite for Cosmology and Astrophysics fostered the hope that relativistic effects could be studied in a large sample of nearby AGNs. This expectation has now been satisfied by XMM-Newton.

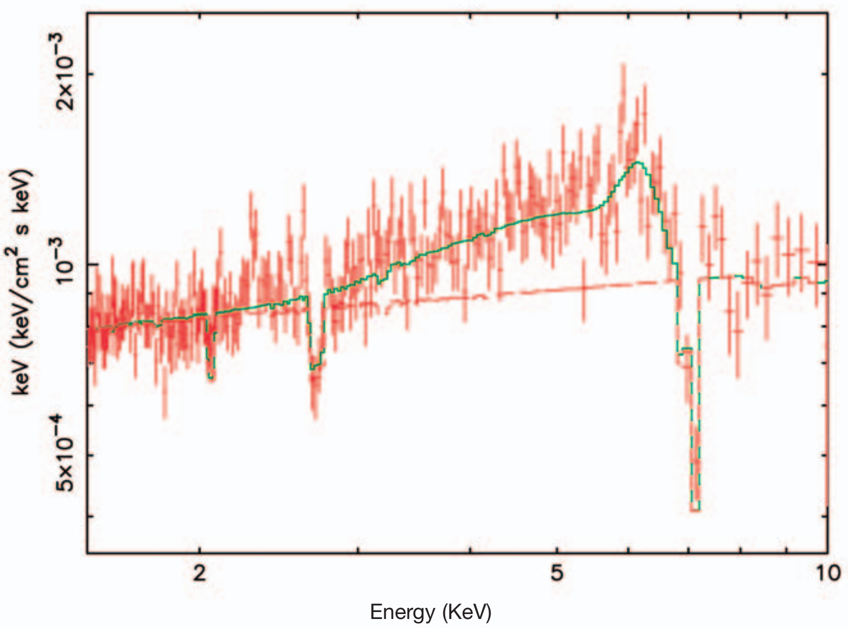
The accompanying figure (next page) shows one example of relativistically broadened and skewed iron K_α fluorescent lines measured by XMM-Newton. Similar profiles were observed for lighter elements such as oxygen, neon and carbon. Each of these measurements probes a specific characteristic of the accretion process onto a black hole. In MCG 6-30-15, energy extraction from a maximally rotating black hole is probably at work. In other AGNs, the line is probably produced in small local flares above the relativistic accretion disk, due to the same kind of magnetic processes that are at work on the Sun’s photosphere.

However, what XMM-Newton has not observed is even more intriguing! Relativistically distorted lines seem to be much less common than expected (and hoped for) prior to the launch of XMM-Newton. The majority of AGNs in the largest sample observed by XMM-Newton so far (53 objects) do show K_α fluorescent iron lines, but their profile is not significantly distorted by relativistic

Top figure: The relativistically distorted K_{α} fluorescent iron-line profile of MCG-6-3-15 measured by XMM-Newton (from A.C. Fabian et al., Monthly Notices of the Royal Astronomical Society, 2002)

Bottom figure: Spectrum of the luminous AGN PG1211+143, showing the absorption lines discovered by XMM-Newton (from K. Pounds et al., Monthly Notices of the Royal Astronomical Society, 2003)





effects. This provides firm proof for the bulk of these emission lines being produced by matter far away from the black hole itself. Consequently, only a small fraction of AGNs look to be suitable as probes of general relativistic effects. It is not clear why super-massive black holes are seemingly so 'shy' in the energy band where their power and glory should be most clearly manifested. It probably has to do with the physical properties of the accretion flow. Matter very close to a black hole could be too hot to be 'sensitive' to fluorescence stimuli.

These new XMM-Newton results are drastically changing the way we look at the behaviour of cosmic gas and dust close to black holes.

Black-Hole Winds

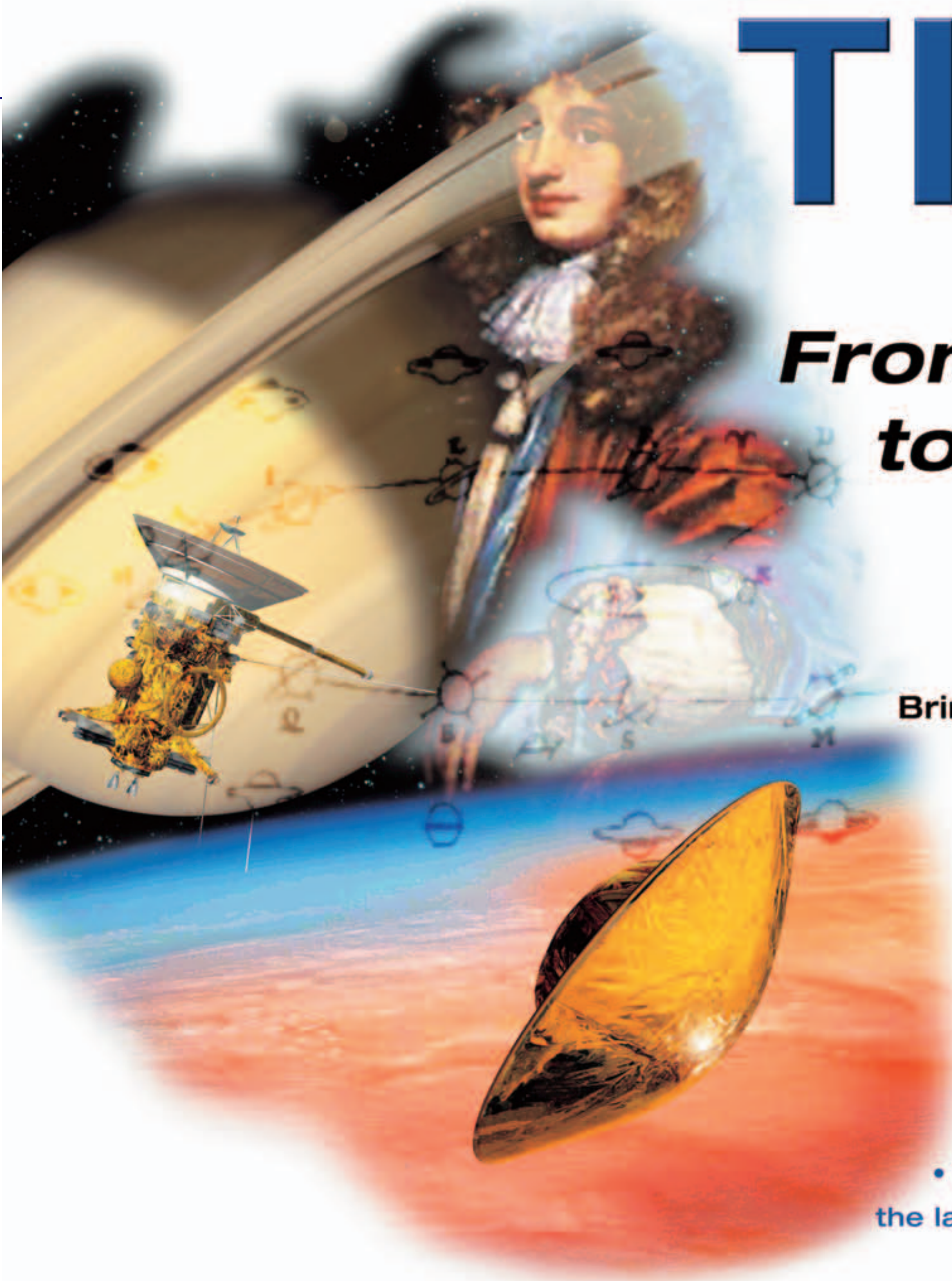
Recently XMM-Newton has discovered deep absorption lines in the spectra of two luminous quasars, PG 0844+349 and PG 1211+143 (see figure). These lines are significantly blue-shifted with respect to the systemic velocity of the host galaxy, suggesting that they occur in an outflow traveling at about one tenth of the speed of light. This evidence has been interpreted as a manifestation of the extraordinary power of black holes to generate relativistic 'winds' of matter, expelled from the cores of active galaxies.

'Intermediate-mass' Black Holes

One may ask why black holes should exist only in 'stellar-mass' or 'super-massive' form. Why isn't there anything in between? In recent years, evidence has been accumulating for the existence of 'Ultra-Luminous X-ray Sources' (ULXs), whose luminosity is significantly larger than that of stellar-mass black holes. One hypothesis is that these systems may be hosting black holes of 'intermediate' mass. XMM-Newton's contribution has been crucial in this field too, since it has clearly demonstrated that at least some of the known ULXs share the same basic qualitative properties with other black-hole accreting systems, such as galactic black holes or AGNs.

Conclusion

Though there turns out to much more in the sky than theoretical astrophysicists can today imagine, XMM-Newton seems very well equipped to discover and study it, even if it is the flickering ghost of a turbulent, elusive and shy black hole!



TITAN

From Discovery to Encounter

Bringing together historians and space scientists to discuss:

- Christiaan Huygens: the man, the scientist, his relationship with other scientists of the day
- Observations of Saturn and its moons since the 17th century
- The Cassini-Huygens missions and the latest observations en route to Titan

13 – 17 April 2004

ESTEC, Noordwijk, The Netherlands

Public day: 17 April 2004

The programme includes:

- Museum excursions
- Musical interludes
- Video of the Cassini/Huygens mission
- A public day with amateur astronomy observations of Saturn and Titan

http://sci2.esa.int/huygens/conference

esa NASA