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XMM-Newton highlights

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Abstract. XMM-Newton is one of the most successful astronomical missions of the European Space Agency. We illustrate the impact of the mission with various scientific highlights covering a wide range of scientific fields from young stars up to cosmology.

Key words. Missions: XMM-Newton

1. Introduction

XMM-Newton (Jansen et al. 2001) is the second cornerstone of ESA's Horizon 2000 Science Programme providing the scientific community with a large X-ray observatory. It was launched by an Ariane 5 launcher in 1999. The spacecraft carries three mirror modules (Aschenbach et al. 2000) each consisting of 58 gold-coated nested Wolter 1 telescopes. XMM-Newton observes simultaneously with six scientific instruments: Three CCD cameras (European Photon Imaging Camera (EPIC) consisting of one pn-camera (Strüder et al. 2001) and two MOS-cameras (Turner et al. 2001) for high throughput non-dispersive X-ray spectroscopic imaging in the energy range from 0.2 keV to 12 keV and two high resolution dispersive spectroscopy (Reflection Grating Spectrometer (RGS, den Herder et al. 2001) in the energy range from 0.4 keV to 2.2 keV. In addition it provides simultaneous optical/UV observations with a co-aligned telescope (Optical Monitor (OM, Mason et al. 2001)).

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2. Overall impact of XMM-Newton and size of its scientific community

The majority of XMM-Newton's observing time is made available to the astronomical community by the traditional route of Announcements of Opportunity, followed by peer review. All ten XMM-Newton "Calls for Observing Proposals" have resulted in an oversubscription of the available observing time by a factor of at least 6.5. Each call typically involves 1400 individual astronomers, which is approximately 15% of all professional astronomers worldwide. At the writing of this report more than 2780 articles based on XMM-Newton data have been published in refereed journals, at a rate which currently exceeds 300 per year. XMM-Newton publications are highly cited; about 40% of its publications belong to the top category of the 10% most quoted astronomical articles. The importance of XMM-Newton is now widely recognized in the scientific world at large, beyond the X-ray and astronomical community. For illustration, *Nature* completed its cycle of review articles honouring the International Year of Astronomy, with a description of

XMM-Newton's and Chandra's achievements (Santos-Lleó et al. 2009).

3. Science highlights

XMM-Newton continuously breaks new ground in many areas of science. In the following we illustrate this with several scientific highlights published in the refereed journals. Many of these highlights are achievements of the last years and were taken from the science case for the XMM-Newton mission extension which is prepared every two years by the author.

3.1. Young and main sequence stars

Major progress was achieved in our understanding of the interplay between accretion processes and X-ray emission in pre-main sequence (PMS) stars. A large observing program of the Taurus Molecular Cloud (Güdel et al. 2007a), the nearest star-forming region, shows that accreting PMS objects are X-ray fainter because infalling cool material mixes with the hot coronae of the stars, thereby cooling this material. The strongly accreting PMS stars can also emit soft X-rays produced in polar jets of material ejected by the star. These results are important in helping to understand the feedback of the X-ray emission on the circumstellar material as well as for the fate of the circumstellar disks and the formation of planets out of these disks. The XMM-Newton survey of the Taurus Molecular Cloud resulted in 15 articles published as a special feature in Astronomy & Astrophysics.

XMM-Newton has substantially contributed to our knowledge of young stellar objects (YSO) and of their interaction with the surrounding circum-stellar disks. During a deep observation of the ρ-Ophiuchi star forming region, XMM-Newton observed fluorescent iron emission lines for a period of four days following a large stellar flare. The iron lines trace magnetic field lines in accretion loops between the star and its disk. While most YSO flares are similar to solar ones, some are occasionally large enough to span the star-disk separation (Giardino et al. 2007; Sciortino 2008; Giardino et al. 2009).

The finding that X-ray emission in classical T Tauri pre-main sequence stars arises from a hot spot suggests that accretion shocks are common features during this evolutionary phase (Stelzer & Schmitt 2004; Schmitt et al. 2005; Güdel & Telleschi 2007b). The first, well exposed, high resolution X-ray spectra of an isolated Herbig Ae/Be star (HD 163296) revealed that the bulk of the soft X-ray emission originates from a low-density gas embedded in a weak UV radiation field (Güther & Schmitt 2009). This was totally unexpected. According to our current understanding of T Tauri stars, one expects that the shock of the accretion flow onto the stellar surface would generate copious amount of soft X-rays. By contrast, the XMM-Newton RGS data indicate that the bulk of the soft X-ray flux originates further away, at a distance of a few stellar radii from the star.

A highlight was the first detection of a cyclic X-ray variation in a solar type star (HD 81809). It is synchronised with the star-spot cycle, similar to that of the Sun (Favata et al. 2004).

3.2. Hot stars

The discovery of diffuse X-ray emission from a million degree gas pervading the Orion nebula came as a surprise (Güdel et al. 2008). This sort of hot plasma is normally only observed in regions with much more vigorous stellar formation and many more massive stars than in Orion. This detection shows that a handful of massive stars is enough to generate an extensive hot bubble through the accumulation of stellar wind losses. This suggests that bubbles of hot gas may be far more common than previously realised.

Another important result was the first detection of faint, hard X-ray emission from a Wolf-Rayet star. The star, WR142, belongs to the rare WO category which is characterized by strong oxygen lines in their optical spectra. Such stars are thought to be in an advanced evolutionary state shortly before their explosion as a supernovae or gamma-ray burst. The discovery of hard X-ray emission sheds new light on the properties of Wolf-Rayet stellar winds and on the last stages of massive star evolution (Oskinova et al. 2009).

3.3. Novae and White dwarfs

While monitoring the centre of the nearby galaxy M31, XMM-Newton uncovered a new class of novae which turn-on and off in only a few months. It was also possible to infer the duration of the on-state for a large sample of novae and the delay between the X-ray and optical outbursts. Both parameters are crucial in determining the mass of the progenitor white dwarf, as well as the mass and composition of its ejecta (Pietsch et al. 2007, 2008).

XMM-Newton observations led to the detection of a white dwarf in the binary system HD 49578 and established its dynamical mass to be 1.2 solar masses (Mereghetti et al. 2009). The system is of particular interest since even a small amount of accretion will be sufficient to drive the white dwarf mass above the Chandrasekhar limit beyond which the star becomes gravitationally unstable and explodes as a type-Ia supernova.

3.4. Gamma-Ray Bursts, Supernovae and Supernovae Remnants (SNR)

Through a combination of efficient planning and spacecraft performance, XMM-Newton is able to quickly respond to targets of opportunity and be on-target some 5 hours after such an initial alert (Schartel et al. 2004). This has led to particular success in the first detection of a time-dependent dust-scattered X-ray halo around a gamma-ray burst (GRB 031203, Vaughan et al. 2004), where the halo appeared as concentric time-dependent ring-like structures centred on the burst location.

A major result was the recognition of a new class of type Ia SN based on the emission of the Fe L-shell lines of the SNR DEM L238 and DEM L249 (Borkowski et al. 2006). This discovery has important cosmological implications, as SN Ia are used as standard candles. Thanks to XMM-Newton spectra, accurate relative elemental abundances could be measured in SNR, which in turn enabled detailed tests of type Ia SNe explosion models. Among them is SNR 0509-67.5 in the LMC for which both optical and X-ray data favour the delayed detonation model for an explosion that occurred some 400 yr ago (Badenes et al. 2008; Kosenko et al. 2008).

Using RGS observations of the rims of bright SNRs such as SN 1006 (Vink et al. 2003), it has been possible to measure ion temperatures directly from line broadening of oxygen lines, and this opens opportunities to test shock equilibration models directly from the observations.

A further highlight was the identification of the radio source G350.1-0.3 with a 900 year old SNR and the detection of the associated left-over neutron star (Gaensler et al. 2008). The identification is an important step toward a complete census of young SNRs in the Galaxy.

The bright remnant of the supernovae from 1006, SN 1006, is the prototype of shell SNR. The comparison of its hart X-ray image (2.0 keV to 4.5 keV) with radio observations let to the identification of the long predicted for non-thermal synchrotron emission and showed that the magnetic field is amplified where electron acceleration is efficient (Rothenflug et al. 2004)). A highlight of SNR observations was the XMM-Newton mapping of RCW 86. Along its north-eastern shell the dominant X-ray radiation mechanism changes from thermal to synchrotron emission (Vink et al. 2006). The derived physical parameters argue strongly for identifying RCW 86 with the remnant of SN 185.

3.5. Neutron stars:

The discovery of bow shocks aligned with the neutron star Geminga's supersonic motion (Caraveo et al. 2003) and the discovery of an 60-meter-radius rotating hot spot on it's surface through phase-resolved spectroscopy (Caraveo et al. 2004) were highly exciting results. The two discoveries together are of fundamental importance as they identify the missing link between the X-ray and gamma-ray emission from neutron stars. Phase-resolved spectroscopy allowed the detection of hot spots on two further neutron stars demonstrating that the magnetic field configurations and surface temperature distributions are significantly more complex than previously anticipated (De Luca et al. 2005). Sinusoidal variations in the X-ray flux and spectral shape of the neutron star RX J0720.4-3125 measured over several years can be understood as precession revealing two hot spots on the stars surface of different temperature, different size and probably not located exactly in antipodal positions (Haberl et al. 2006).

High resolution spectra of the ultra-compact X-ray binary 4U 1543-624 let to the first detection of a relativistically distorted oxygen (O VIII Lyα) emission line which is explained by X-rays reflected off the accretion disc in the strong gravitational field close to the neutron star (Madej et al. 2011). Measurements of the cooling curves of transient, thermally emitting, neutron stars have yielded important insights into the physical processes in their very high density cores. Combining these diagnostics with those obtained from models of neutron star atmospheres has allowed strong constraints on the equation of state of dense nuclear matter to be set (Webb & Barret 2007).

Central compact objects (CCO) are isolated neutron stars embedded in a SNR. XMM-Newton data allowed the detection of a strong periodic modulation of the X-ray flux of the CCO in the 2000 year old SNR RCW 103. The modulation may be explained either with an X-ray binary or a peculiar magnetar(De Luca et al. 2006). However, both scenarios require nonstandard assumptions illustrating the progressing discussion about the nature of this object class. XMM-Newton and Chandra data were used to infer the spin-down rate in the CCO pulsar PSR-J1852+0040 (Halpern & Gotthelf 2010). This led to the first determination of the magnetic field in a CCO, 3.1 1010 G, the smallest ever measured for a young neutron star. This provides strong support to the "anti-magnetar" model whereby CCO are borne with a slow rotation rate which prevents them from developing a strong magnetic field.

Direct probes of the physical processes at work in the most magnetized isolated neutron stars (magnetars) have been obtained with XMM-Newton (Rea et al. 2008). These results support the twisted magnetosphere model, revealing the coupling between the internal magnetic field and the neutron star crust. A huge surprise was the finding of a Soft-Gamma-Repeater with a very low magnetic field based on measurements of XMM-Newton and other X-ray satellites (Rea et al. 2010). This finding rejects the hypothesis that strongest magnetic fields are a prerequisite for the emission of (soft) Gamma-Ray-Bursts.

3.6. Galactic Black holes

A black hole was found in a globular cluster associated with the nearby elliptical galaxy NGC 4472 (Maccarone et al. 2007). This is the first detection of a black hole in a globular cluster. The existence of this black hole has direct implications for the understanding of the formation and evolution of globular clusters. XMM-Newton observations of the X-ray source HLX-1 in the spiral galaxy ESO 243-49 yielded the first solid evidence for the existence of intermediate-mass black hole (Farrell et al. 2009). They are characterised by masses intermediate between those of stellar mass black holes (< 100 Mo) and AGNs (10^5 M_o). Their existence had been long predicted, but firm observational confirmation had been hard to come by. Large luminosity variations measured in HLX-1 allow setting a conservative lower limit on its mass of 500 Mo. It is worth noting that HLX-1 was discovered serendipitously by XMM-Newton.

3.7. Supermassive black holes and active galactic nuclei (AGN)

XMM-Newton observation of the active galaxy RE J1034+396 yielded the first detection of quasi-periodic oscillations in a super-massive black hole (SMBH) (Gierliski et al. 2008). Such oscillations are of fundamental importance since they provide a natural length scale of the system. They are frequently observed in stellar mass black holes, but had so far eluded detection in AGN's. The 3730 s quasi-period measured in REJ 1034+396 fits nicely the time required to complete one revolution in the last stable orbit around a 10 million solar mass black hole. XMM-Newton's high effective area allowed the detection of a transient redshifted emission feature in the X-ray spectra of a two bright highly variable Seyfert galaxies (eg. Mrk 766 Turner et al. 2006 and NGC3516 Iwasawa, Miniutti & Fabian 2004), showing flux modulation over time intervals of the same order as, or shorter than, the XMM-Newton exposure. The evolution of such a feature agrees with an iron emission from a spot in the inner regions of an accretion disk illuminated by a co-rotating flare.

An eight-day observation of the narrow-line Seyfert 1 galaxy 1H 0707-495 with XMM-Newton led to the first detection of a relativistically distorted iron L emission line in an AGN (Fabian et al. 2009). Intensity variations of the iron L line were found to lag those of the direct X-ray continuum by 30 s, as expected in the disk reflection model where iron lines are produced by fluorescence from continuum photons reflected off the disk. The 30 s delay thus provides a direct measure of the inner radius of the accretion disk which can in turn be used to infer the mass of the black-hole, 7 million solar masses. (See also Zoghbi et al. 2010, Miller et al. 2011 and Zoghbi, Uttley & Fabian 2011).

The optical monitor onboard of XMM-Newton allowed for the first time the determination of simultaneous spectral energy distributions (SED) for the majority of the Peterson & Horne (2004) reverberation mapped sample of AGNs. These simultaneous SEDs reveal a distribution which is significant different from the SED distributions generated based on non-simultaneously observed data (Vasudevan & Fabian et al. 2009). Spectacular sets of XMM-Newton spectra of NGC 4051 have yielded direct measurements of the total power released by AGN winds, and provided strong evidence that these play an important role in controlling the formation of structure in the Universe (Krongold et al. 2007).

3.8. Groups and clusters of galaxies:

XMM-Newton observations allow the generation of brightness, temperature and entropy maps for clusters of galaxies, which allow the study of various physical mechanisms of clusters grow. Examples are the dynamics of cluster mergers in A754 (Henry, Finoguenov & Briel 2004), the first direct X-ray evidence of shock heating in a merging cluster (RXCJ0658.5-5556) (Finoguenov, Böhringer, & Zhang 2005) and the observation of warm gas (colder than the cluster gas) flows into the cluster from a large-scale structure filament in RXCJ 0232.2-4420.

The absence of a strong cooling flow for low temperatures in three clusters of galaxies (Peterson, et al. 2001; Tamura et al. 2001; Kaastra et al. 2001) was an early key result of XMM-Newton which lead to the AGN feedback scenario which physically connects the three main extragalactic object classes, i.e. galaxies, clusters of galaxies and AGNs, and explains their grows and evolution over cosmological times. The AGN feedback has the potential to play for extragalactic astronomy a similar fundamental role as the nuclear fusion plays for the physical understanding of the live and evolution of stars.

Deep XMM-Newton observations of the COSMOS 2 deg^2 field led to the detection of 206 groups of galaxies with redshifts of up to 1. This large sample was used to investigate the scaling relation between the X-ray luminosity, L_x, and the halo mass, M_H, of the galaxy groups, where M_H represents the total mass of the group inferred from weak gravitational lensing techniques. The L_x/M_H relation had so far been established only for large groups and clusters of galaxies in the local Universe. This new study (Leauthaud et al. 2010) extends its validity to much smaller halos and higher redshifts. The mass-luminosity relation is an important tool for cosmology and the study of structure evolution in the Universe.

High resolution spectra allowed obtaining the first limit on the turbulent velocity of the intracluster medium in the core of a cluster of galaxies. The 90% - upper limit on non-thermal velocity broadening of Abell 1835 is 274 km s^{-1} which corresponds to a turbulent to thermal energy density <13%. Therefore, it can be expected that the turbulent energy density plays only a minor role in clusters energy budget (Sanders et al. 2010).

An important aspect of galaxy feedback is the ICM enrichment via supernovae driven galactic winds. Accurate abundances measurements are possible with XMM-Newton. The analysis of Sersic 159-03 and 2A 0335+096 provided strong new constrains on the abundances of supernovae explosions, i.e. the intergalactic medium was generated to 30% in SN Type Ia and to 70% in core collapse explosions (Werner et al. 2006; de Plaa et al. 2006, 2007).

X-ray observations from XMM-Newton alone or in combination with near IR observations increased several times the maximal redshift at which the most distant (mature) cluster was found: In 2005 XMMU J2235.3-2557 was detected with z=1.39 (Mullis et al. 2005), in 2006 XMMXCS J2215.9-1738 was found at z=1.45 (Stanford et al. 2006) and in 2010 SXDF could be indentified with z=1.62 (Tanaka, Finoguenov & Ueda 2010). Currently, CL J1414+0856 is the most distant mature cluster of galaxies with z=2.07 (Gobat et al. 2011). This cluster has a mass comparable with Virgo demonstrating that such objects can form significantly early form as previously known.

Using the newly released "mosaic" observing mode, XMM-Newton recently mapped two new galaxy clusters one of which, SPT-CL J2332-5358, is among the hottest (1.1 108 K) and most massive (10^{15} M_o) clusters known to date. The clusters were tentatively discovered with the South-Pole Telecope but XMM-Newton observations were essential to confirm the discovery and to characterise the clusters (Šuhad et al. 2010). This illustrates the power of combining mm and X-ray observations for finding and characterising clusters of galaxies.

3.9. Intergalactic medium and dark matter

XMM-Newton uncovered the first evidence for the long sought "cosmic web", the dilute and warm-hot intergalactic medium (WHIM) which is expected to contain half of the baryons in the local Universe. Because of its low emissivity, the WHIM had so far escaped detection. The filament detected by XMM-Newton connects the pair of clusters Abell 222 & 223 and has a temperature of 10^7 K (Werner et al. 2008).

By combining high resolution grating spectra from XMM-Newton and Chandra it has been possible for the first time to find direct and unambiguous observational evidence for the long sought after WHIM. The cosmological importance of the WHIM is twofold: not only does it contain most of the baryonic mass in the local Universe, but it also acts as a tracer of large scale structure. However, its temperature and very low density make it very difficult to detect with current facilities. The WHIM was detected by the O VII absorption line imprinted on the spectrum of a distant source the blazar H 2356-309 (Buote et al. 2009; Fang et al. 2010). At a redshift of 0.03, the absorption originates in the Sculptor Wall, a large scale superstructure of galaxies in the nearby Universe.

XMM-Newton surveyed the COSMOS HST 2-degree^2 field (Hasinger et al. 2007), the largest survey undertaken with HST. The combination of XMM-Newton and HST data and ground-based redshifts has resulted in the first 3-dimensional map of dark matter across the COSMOS field and extending back in time by about six billion years. The 3-D X-ray map has shown that normal matter, as evidenced by X-ray emitting clusters of galaxies, accumulates along the densest concentrations of Dark Matter which is seen to have grown increasingly clumpy in the local Universe (Massey et al. 2007).

Dark matter concentrations like clusters of galaxies or M31 allowed the determination of upper-limits for hypothetical decay lines of sterile neutrinos strongly constraining the particle's parameter range (Boyarsky et al. 2006, 2008).

3.10. Catalogues:

Two catalogues of serendipitous sources are updated regularly: the 2XMM catalogue (Watson et al. 2009) currently contains 353,000 X-ray detections of 263,000 individual sources, making it the largest X-ray catalogue ever. The X-ray Slew Catalogue Saxton et al. (2008) contains 11,400 sources and covers 48% of the entire sky. Finally, the XMM-OM Serendipitous Ultraviolet Source Survey contains 753,000 UV detections with the Optical Monitor from 624,000 unique sources.

4. Science potential

The February 2008 issue of Astronomical Notes contains 26 articles presented at the workshop “XMM-Newton: The next decade” (Schartel et al. 2008; McBreen & Schartel et al. 2008) where the authors outline several innovative research programs that require the unique capabilities of XMM-Newton.

Understanding the formation of stars and planetary systems in various environments is one of the key topics in contemporary astrophysics. The combination of spectroscopic diagnostics from Herschel and XMM-Newton will continue to provide unique insights into the accretion and outflow processes and the relationship between the two, as well as into the role played by magnetic fields in protostars and the formation of young stellar systems. Similarly, combining ALMA and XMM-Newton results will provide complementary views on the effects of stellar radiation on proto-planetary disks.

The October 2006 issue of Astronomical Notes was devoted to relativistically broadened iron lines emitted in the vicinity of black holes (Schartel et al. 2006), where strong gravitational fields affect the physics of line production and their variability. Several authors stress the unique ability of XMM-Newton to provide long, uninterrupted, high signal-to-noise time series which are essential for this type of investigation.

As demonstrated by the recent detection of WHIM from the Sculptor Wall (Buote et al. 2009; Fang et al. 2010), XMM-Newton continues to open new avenues of research even ten years after its launch. Since the spectral features imprinted by the WHIM are quite faint, the high throughput of XMM-Newton will be essential to secure the high-quality spectra required for the first detection of “free” WHIM.

Combining XMM-Newton observation with data from new facilities such as Planck, LOFAR, ALMA and the South Pole Sunyaev-Zel’dovich (SZ) survey will significantly advance our understanding of dark matter, structure formation, and dark energy. Planck will provide a unique and complete sample of massive clusters up to a redshift of about one which will be a powerful tool for precision cosmology. XMM-Newton observations will be crucial in exploiting this sample.

5. Discussion

ETTORE DEL MONTE: Which is the health status of the XMM-Newton satellite and how long, in your opinion, will it continue to work?
NORBERT SCHARTEL: XMM-Newton is in excellent health. For all essential spacecraft and instrument components we still have redundancy. XMM-Newton operations are extended every two years by a two plus two years schemata, i.e. XMM-Newton operations are founded for two years plus resources for two further years are allocated which are subject to midterm confirmation. From the technical side fuel is the lifetime limiting consumable, which is used for angular momentum dumping. Given the current consumption XMM-Newton can operate up to 2020. During the next two years the mission intents to investigate a new operation mode which uses the fourth reaction wheel onboard in addition to the three reaction wheels currently in use. This mode has the potential to extend the mission lifetime to 2026.

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