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TWENTY YEARS OF XMM-NEWTON

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Abstract. *XMM-Newton*, a large X-ray observatory launched by the *European Space Agency* (ESA), will be 20 years old in 2019. This cornerstone mission from ESA's *Horizon 2000 programme* continues to make ground breaking discoveries twenty years after its launch. Thanks to its sensitivity and wide field of view, *XMM-Newton* has studied hundreds of thousands of stars and active galactic nuclei (AGN), as well as rarer objects such as galaxy clusters, supernova remnants, X-ray binaries, ultra luminous X-ray sources (ULXs), exoplanets and even the aurora on planets within our solar system. Since the conception of *XMM-Newton*, France has played an important role in this flagship mission, initially in developing the instruments carried on board and since 1996 in the ground segment activities (*XMM-Newton Survey Science Centre*). Here we will review some of the more notable results from this observatory and discuss the outlook for the future with *XMM-Newton* and the next ESA large X-ray observatory, *Athena*.

Keywords: X-rays: general, Telescopes, Surveys, Catalogs

1 Introduction

XMM-Newton is the *European Space Agency's* second cornerstone mission from the *Horizon 2000 programme* (Jansen et al. 2001). *XMM-Newton* was launched on 10th December 1999 and as result, will celebrate its twentieth birthday in 2019. It has the largest effective area of any X-ray satellite (Longinotti 2014), thanks to its three X-ray telescopes observing in the 0.2-12.0 keV domain, each with $\sim$1500 cm^2 of geometric effective area. The field of view (FOV) is 30' and provides an angular resolution of arcseconds. Behind each of the X-ray telescopes is one of the three *European Photon Imaging Cameras* (EPIC) (Strüder et al. 2001; Turner et al. 2001), built by a collaboration of Italian, British, French and German scientists. The three detectors are a pn camera and two Metal Oxide Semi-conductor (MOS) cameras, spectro-imagers which can reach a time resolution of tens of microseconds. Only half of the X-ray flux falls on the MOS cameras, where the other half is directed towards the Reflection Grating Spectrographs (RGS, den Herder et al. 2001), built by a Dutch, British, American and Spanish collaboration. These provide high spectral resolution (from 100 to 500, FWHM) X-ray spectroscopy in the energy range 0.33-2.5 keV or 5-38 Å. In addition there is a complimentary ultra-violet and optical telescope called the *Optical Monitor* (OM Mason et al. 2001), built by a British, American and Belgian collaboration, that covers 17', and is centred on the same point as the X-ray telescopes. The observatory is open to all through yearly calls for proposals. Data is accessed via the XMM-Newton Science Archive*.

The *XMM-Newton Survey Science Centre*† (SSC), a consortium of ten European Institutes (Watson et al. 2001) led by *IRAP* in Toulouse, was selected by ESA in 1996 to ensure that the scientific community can exploit the data accumulated by *XMM-Newton*. The SSC has developed much of the *XMM-Newton Science Analysis Software* (SAS) (Gabriel et al. 2004) for reducing and analysing *XMM-Newton* data and created pipelines to perform standardised routine processing of the *XMM-Newton* science data. The XMM-SSC also produces catalogues of detections made with the *EPIC* cameras and the OM. These catalogues are excellent resources that can be used for a wide variety of astrophysical research such as for accessing source data and products, finding new objects, studying homogeneous populations of objects and for cross-correlation with multi-wavelength data.

In this short review we will discuss results stemming from both the French and the international X-ray community. These will cover a wide variety of objects observed with *XMM-Newton*, from exoplanets to galaxy clusters. The salient points of the *XMM-Newton* catalogues will also be presented, before looking to the future with both *XMM-Newton* and *Athena*.

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†`http://xmmssc.irap.omp.eu/`

2 Highlights from the past twenty years

2.1 Stars and planets

Young, low-mass stars are X-ray bright due to considerable magnetic activity. X-rays are emitted by high temperature plasma which is heated during magnetic reconnection events (e.g. Ozawa et al. 2005). The great sensitivity and wide field of view makes XMM-Newton the ideal satellite to observe nearby active star forming regions as a significant part of the area can be observed in a single pointing. The star forming region ρ Ophiuchi was one of the first such fields to be pointed during the first month of observations with *XMM-Newton*. 87 X-ray sources were detected including 25 previously unknown X-ray sources (Ozawa et al. 2005). 15 of these were classified as class III (weak-lined T Tauri stars) sources, doubling the population of these objects known at the time of the observations. During this short pointing of only 30 ks, one of the two brown dwarfs detected was shown to be flaring, where this is likely to be due to solar-like magnetic activity.

XMM-Newton has been used to observe many solar system objects, such as the aurora on Jupiter (e.g. Dunn et al. 2017), or solar wind charge exchange on Mars (e.g. Koutroumpa et al. 2012) or even various comets (e.g. Schulz et al. 2006), but it is now also being used to understand exoplanets (King et al. 2018). A planetary transit of a hot Jupiter in the system HD 189733 was observed with *XMM-Newton* (Poppenhaeger et al. 2013). Marin & Grosso (2017) propose that a direct detection in X-rays of the exoplanet would not be possible, but the ultra-violet domain using the OM offers further possibilities to observe planets/transits (King et al. 2018).

2.2 Supernova remnants

The high collecting area and wide field of view are particularly well suited to studying supernova remnants, for example the 439 ks good time interval observations of the supernova remnant SN 1006 (Li et al. 2015). From this dataset, Li et al. (2015) extracted and analysed spectra from 3596 tessellated regions, each with at least 10^4 counts (0.3-8 keV band). This high signal to noise ratio data enabled them to map out multiple physical parameters, such as the temperature, electron density, ionization parameter, ionization age and metal abundances and allowed them to deduce an asymmetric metal distribution across the remnant. They suggested that this implies either an asymmetric explosion of the supernova or an asymmetric distribution of the interstellar medium, amongst other results.

The good angular resolution also allowed Acero et al. (2017) to measure the expansion of the supernova remnant RX J1713.73946 using *XMM-Newton*. RX J1713.73946 is the brightest supernova remnant at TeV energies and is often thought of as the prototypical cosmic ray accelerator. From the measurements they determine both the current density at the shock and the age of the remnant.

2.3 The Galactic centre

Almost 600 observations have been consecrated to the understanding of the Galactic centre region, and 8% of the detections in 3XMM-DR8 (or ∼62000 detections) are found in this high density region. A lot of work has gone into identifying these sources. Using 26 of the observations below a Galactic latitude of 20°, 1319 sources were detected (Nebot Gómez-Morán et al. 2013), of which 316 sources were identified thanks to multi-wavelength data. Many of these sources are not actually in the Galactic centre but are late-type active stars situated at less than 1 kpc from the Sun. The population includes 2 cataclysmic variables, 3 T Tauri stars, Herbig-Ae stars, γ-Cas-like objects, 3 X-ray binaries as well as 37 extra-galactic sources at the higher latitudes.

The supermassive black hole at the centre of our galaxy Sgr A* is extremely faint compared to other supermassive black holes in other galaxies (10^{-9} of the Eddington luminosity). A lot of effort has been invested in understanding the low luminosity, as well as the frequent X-ray flares observed (e.g. Mossoux & Grosso 2017). These could be due to a shock produced by the interaction between orbiting stars and a hot accretion flow, a Rossby instability producing magnetised plasma bubbles in a hot accretion flow, an additional heating of electrons near the black hole due to processes such as accretion instability or magnetic reconnection, an increase of the accretion rate when material reaches the close environment of the black hole, or even tidal disruption of asteroids (see Mossoux & Grosso 2017, and references therein), but their origin remains to be demonstrated.

In order to make headway in understanding the luminosity of Sgr A*, Terrier et al. (2018); Ponti et al. (2015); Clavel et al. (2013) and others showed that temporal variability observed in X-ray luminosity of molecular clouds near the Galactic centre were evidence for previous irradiation from Sgr A* during active periods in its past, when it showed flares at least one hundred times brighter than today over the last few hundred years. This is evidence that Sgr A* may have been significantly brighter during its past.

2.4 The growth of supermassive black holes

Supermassive ($\sim 10^{6-10}$ $M_\odot$) black holes (e.g. Lynden-Bell 1969) like Sgr A* are present in the cores of massive galaxies. Whilst hundreds of thousands are known, it is not yet clear how supermassive black holes (SMBH) are formed and evolve. It is unlikely that they form from stellar mass black holes, as even continuously accreting at the Eddington limit, it is difficult to reach masses as high as $\sim 10^9$ $M_\odot$ observed in a massive quasar at z$\sim$7.1 (Mortlock et al. 2011) or the 8×10^8 $M_\odot$ black hole found at z=7.54 (0.69 Gyr, Bañados et al. 2018). Different theories propose that smaller, intermediate mass black holes (IMBH, 10^{2-5} $M_\odot$) would either merge and/or accrete to create SMBH (see Volonteri 2012; Greene 2012; Mezcua 2017, for reviews). This may be at or above the Eddington rate, although the physical mechanism for super-Eddington accretion is still to be elucidated. In order to validate these mechanisms, it is necessary to find intermediate mass black holes and/or determine the mechanism for prolonged super-Eddington accretion.

The *XMM-Newton* catalogue revealed the first good IMBH candidate 2XMM J011028.1-460421, more commonly known as Hyper Luminous X-ray source 1 (HLX-1, Farrell et al. 2009; Godet et al. 2009; Webb et al. 2010). It has a mass of $\sim 10^4$ $M_\odot$ (Godet et al. 2012) and is thought to be accreting periodically by tidally stripping a companion star at periastron in a highly elliptical orbit (Lasota et al. 2011; Godet et al. 2014; Webb et al. 2014), thus making it an exceptional system. However, IMBH can also exist in the centres of lower mass galaxies, but these are often faint and difficult to detect. Nonetheless, they can tidally disrupt a passing star, causing the system to become brighter by several decades in luminosity in X-rays and at other wavelengths, making them easier to locate. These tidal disruption events (TDEs) can also go periods of super-Eddington accretion, making them interesting to study to help understand the formation of supermassive black holes. Many TDEs have been identified through exploring *XMM-Newton* data, e.g. Lin et al. (2011); Saxton et al. (2015); Lin et al. (2017a); Saxton et al. (2017); Lin et al. (2018). Some show evidence for IMBHs, i.e. the black hole in the centre of the inactive galaxy IC 4765-f01-1504 which showed a TDE in 2006. The mass of the black hole has been estimated to be 6×10^4 - 4×10^6 $M_\odot$ (Lin et al. 2011). Another TDE occurred around the massive black hole in a dwarf galaxy orbiting 6dFGS gJ215022.2-055059. The mass of this black hole has been estimated to be $5.3 \times 10^4 < M_{BH} < 1.2\times 10^5$ $M_\odot$ (Lin et al. 2018). Another TDE was identified showing super-Eddington accretion over more than 10 years (Lin et al. 2017b), demonstrating that it is possible to fuel supermassive black holes at high rates for long periods.

2.5 Galaxy clusters

Galaxy clusters are the largest bound gravitational structures in the Universe. They group together to form the large scale structure of the Universe. They are also known to contain significant amounts of dark matter, the nature of which is still unknown. In order to understand how matter is structured across the Universe and get an insight into the nature of dark matter, and constrain cosmological models, it is necessary to identify galaxy clusters across time. In order to do this a very large programme was initiated (the *XMM-Newton Large Scale Structure Survey*, XMM-LSS Pierre et al. 2004). This programme was then enlarged to become the XXL programme (Pierre et al. 2016) which was composed of 542 *XMM-Newton* observations, each of at least 10ks, totalling 6.9 Ms, as well as complimentary multi-wavelength data. This mapped two extragalactic regions of $25^{\circ 2}$. The main goal of the project is to constrain the Dark Energy equation of state using clusters of galaxies. More than 26000 sources have been found in the survey, where the majority are AGN (Chiappetti et al. 2018). Including other publicly available observations, XCLASS (Clerc et al. 2012), has examined 4200 observations at high latitudes in which 1500 galaxy clusters have been identified.

Other surveys based on public *XMM-Newton* observations, include the one based on Stripe 82 (Takey et al. 2016) which also has a wide range of multi-wavelength data. Of the 54 clusters with spectroscopic redshifts they find two strong candidates for newly discovered cluster mergers at redshifts of 0.11 and 0.26. Further, since 2018, the 3 Ms over three years XMM heritage cluster project has started. This programme is focused on the products of structure formation in mass and time: a large, unbiased, signal-to-noise limited sample of 118 galaxy clusters detected by Planck via their Sunyaev-Zel'dovich effect. The project aims are[‡] (i) obtain an accurate vision of the statistical properties of the local cluster population, and in the highest mass regime; (ii) uncover the provenance of non-gravitational heating; (iii) measure how their gas is shaped by the collapse into dark matter haloes and the mergers that built today's clusters; (iv) resolve the major uncertainties in mass determinations that limit cosmological inferences; (v) build the foundation for cluster science with next-generation surveys.

[‡] http://xmm-heritage.oas.inaf.it/

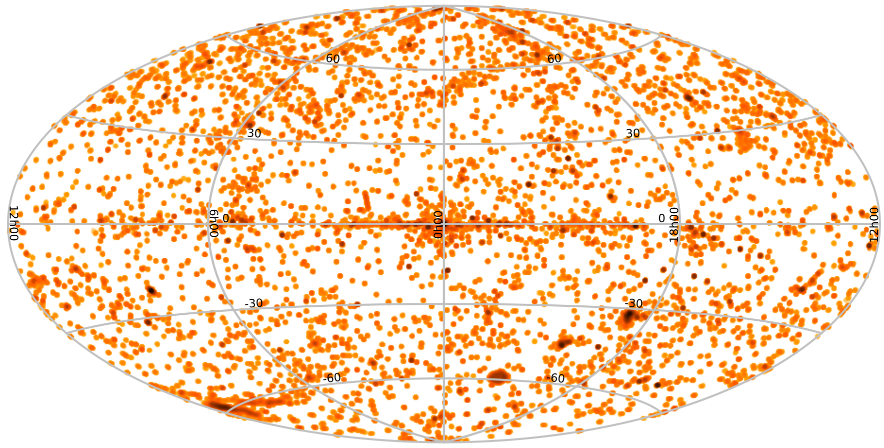

Fig. 1. The detections in the 3XMM-DR8 catalogue shown in a Hammer-Aitoff projection. The darker the colour, the greater the number of observations.

3 The XMM-Newton catalogues

3.1 The catalogue of detections

The catalogues of EPIC detections have been designated 1XMM, 2XMM and 3XMM (Watson et al. 2009; Rosen et al. 2016), with incremental versions of these catalogues indicated by successive data releases, denoted -DR in association with the catalogue number. The most recent version of the catalogue is 3XMM-DR8. It was released in May 2018[§]. It contains 775153 X-ray detections, where objects have been detected as many as 59 times over 17 years from Feb. 2000 to Nov. 2017. 332 columns of information are provided for each detection, including coordinates, observation date, time and mode, exposure and background information, counts, fluxes and rates in 7 energy bands, maximum likelihoods of detection, quality and variability flags, as well as multi-band images, lightcurves and spectra. The distribution of X-ray detections on the sky can be seen in Fig. 1.

3.2 The stacked catalogue

The SSC also produces stacked catalogues of sources. The first of these was 3XMM-DR7s[¶] (Traulsen et al. 2019), released in July 2018. For each source identified from the stacked sources, information regarding the source (similar to that given in the catalogue of detections) is provided, along with a long term lightcurve, allowing easy access to the long term variability of sources. 3XMM-DR7s was compiled from 1789 overlapping good-quality XMM-Newton observations and it contains 71951 unique sources and almost 11000 new sources compared to the single fields used in 3XMM-DR7, thanks to the deeper images obtained through stacking. The effects of stacking and the improvement in the depth of the flux can quite clearly be seen in Fig. 2.

3.3 The OM catalogue

The OM catalogue called the Serendipitous Ultraviolet Source Survey (SUSS) with successive versions designated SUSS-1 - SUSS 4, with SUSS4 the latest version containing 8.17 million detections or 5.5 million unique sources. More than a million of these sources have been detected at least twice. Data is given for the six optical and ultra-violet filters (U, B, V, UVW1, UVM2 and UVW2, Page et al. 2012).

[§] `http://xmmssc.irap.omp.eu/Catalogue/3XMM-DR8/3XMM_DR8.html`
[¶] http://xmmssc.irap.omp.eu/Catalogue/3XMM-DR7s/3XMM_DR7stack.html

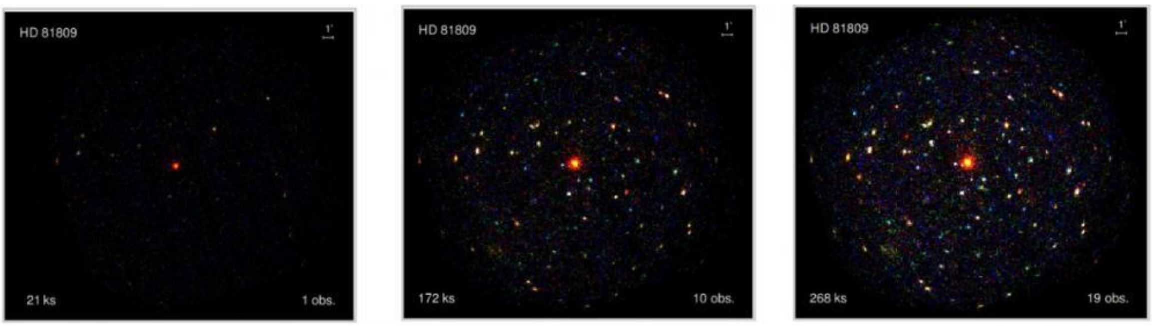

Fig. 2. An example from the stacked catalogue. Left, a single 6 hour observation, middle, 10 observations combined from the same sky region (total of 48 hours of observation), right, 19 observations combined (more than 3 days of data).

4 Future observations

4.1 XMM-Newton

XMM-Newton continues to function nominally, with very little degredation over the last 20 years. *XMM-Newton* has sufficient fuel to continue to function in a similar manner for another ten years. This will allow a larger region of the sky to be surveyed and provide time for deeper observations of sources of particular interest, especially through the new heritage programmes. Building on the current joint programmes, *XMM-Newton* will benefit from joint (and follow-up) observations associated with new space missions and ground facilities, for example, *eROSITA, Euclid*, the *Cherenkov Telescope Array* (CTA), the *Transiting Exoplanet Survey Satellite* (TESS), the *Extremely Large Telescope* (ELT) and the *James Webb Space Telescope* (JWST).

As 2019 comes to a close, we are in the final stages of producing 4XMM-DR9 (the latest release of the EPIC detections catalogue) and 4XMM-DR9s (the latest release of the stacked catalogue). These catalogues benefit from a re-reduction of the all the 14041 observations taken since the beginning of the mission using the latest software, improved calibration and innovative ideas. As with previous versions of 3XMM, these catalogues will be updated on a yearly basis. Improved SUSS catalogues will also be provided in the years to come, taking advantage of improved calibration and new observations.

4.2 Athena

Looking to the future, *Athena* (Advanced Telescope for High ENergy Astrophysics) is the next Large X-ray observatory to be launched by ESA, in the framework of its Cosmic Vision programme. It is expected to be launched in 2032 and has two main science goals, to study the *hot* and the *energetic* Universe. *Athena* will study how hot baryons assemble into groups and clusters of galaxies, determine their chemical enrichment across time, measure their mechanical energy and characterise the missing baryons which are expected to reside in intergalactic filamentary structures. *Athena* will also study the physics of accretion onto compact objects, find the earliest accreting supermassive black holes and trace their growth even when in very obscured environments, and show how they influence the evolution of galaxies and clusters (Nandra et al. 2013).

Athena will consist of a single large-aperture grazing-incidence X-ray telescope, using silicon pore optics. The 12m focal length will provide 5” on-axis angular resolution (half energy width). The focal plane contains two instruments. One is the Wide Field Imager (WFI) which will provide spectro-imaging in the 0.2-15 keV energy band over a 40’ $\times$ 40’ field of view (Rau et al. 2016). The other is the innovative X-ray Integral Field Unit (X-IFU). The X-IFU is a cryogenic X-ray spectrometer, based on a large array of Transition Edge Sensors (TES), offering 2.5 eV spectral resolution, with 5” pixels, over a field of view of 5’ (Barret et al. 2018).

The sensitivity gain of more than a factor of ten, coupled with excellent spectral resolution and wide field of view will revolutionise our understanding of objects that we know of today and discover many new ones besides.

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